TECHNOLOGY WORKSHOP ON LASER BEAMED POWER

From Earth to the Moon and Other Applications

Proceedings of the
February 5, 1991 Workshop
NASA Lewis Research Center
Cleveland, Ohio

NASA

National Aeronautics and
Space Administration

Office of Aeronautics, Exploration
and Technology

Washington, D. C. 20546

TECHNOLOGY WORKSHOP ON LASER BEAMED POWER

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National Aeronautics and
Space Administration.

Lewis Research Center
Cleveland, Ohio
44135

NASA

January 31, 1991

Reply to Attn of. 5430

Dear Colleagues:

I would like to thank all of you for taking time out of your busy schedules to attend to our "Technology Workshop on Laser Beamed Power: From Earth to the Moon and other Applications." We value your presence in our workshop because of your long-standing contributions in the area of space exploration and technology. During this workshop we will have the opportunity to exchange ideas and learn more about the maturity of various laser beam power technologies and systems developed under the SDIO and DARPA sponsorship that might have direct applicability to some of the Agency's needs. We would like to utilize this event as a starting point to further assess the impact of this concept to the Space Exploration Initiative in particular.

For your convenience, I have blocked out 15 rooms at the Harley Airport West Hotel, only 15 minutes away from Lewis Research Center. They will provide you with transportation from the airport to the hotel the evening of February 4 (upon request). Transportation will also be provided on February 5 by the Harley Hotel, departing the hotel at 7:15 AM to our premises and back to the airport at the end of the meeting (5:30 PM). I would encourage you to make your own reservations ASAP by calling the Harley Airport West Hotel at (216) 243-5200. The rate is $57 per room. We are also asking for a contribution of $10 per person to cover for some of the workshop expenses. We will provide a continental breakfast starting at 7:30 AM and a lunch buffet at 12:00 PM.

As a reminder, this activity will be held at the premises of the Aerospace Technology Park, just across the road from Lewis's West Gate, Building AAC, Room 149. Do not hesitate to call me if you have any questions at (216) 433-5154. We are counting on your presence.

Sincerely,

Jose L. Christian, Jr.
Electrical Components and Systems Branch

2 Enclosures:
Workshop Agenda
Map

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TECHNOLOGY WORKSHOP ON LASER BEAMED POWER
From Earth to the Moon and other Applications
NASA LEWIS RESEARCH CENTER
Cleveland, Ohio
February 5, 1991

AGENDA

Morning Session

Time	Topic	Speaker	Affiliation
7:30 AM	Continental Breakfast		
8:00 AM	Welcome & Introduction	Stuart Fordyce	NASA LeRC
8:15 AM	Chartering & Comments to the Panel	John Rather	NASA HQ
8:30 AM	From Earth to the Moon via Laser Beams.	John Rather	NASA HQ
9:15 AM	Free Electron Laser Development	Dan Goodman	SRL, Inc.
9:45 AM	Break		
10:00 AM	Progress in Segmented Mirror Technology — Segment Development for SDI/DARPA	Greg Ames	Kaman Sciences Corp.
10:20 AM	Control of Adaptative Optics Technology	Albert Lazzarini	Kaman Sciences Corp.
10:45 AM	SDIO/DARPA Adaptive Optics and Relay Mirror Experiments	D. Greenwood	Lincoln Lab.
11:45 PM	Lunch		

Afternoon Session

Time	Topic	Speaker	Affiliation
1:00 PM	Laser Powered Orbital Transfer Vehicles — Laser Electric Propulsion: Mission Analysis	Grant Logan	LLNL
1:30 PM	SOA Electric Propulsion Technology	Dave Byers	NASA LeRC
2:00 PM	Laser/Photovoltaic (PV) Technology — PV State-of-the-Art Technology	Geoff Landis	LeRC/Sverdrup
2:30 PM	Laser/PV Qualification Experiment	Ed Coomes	Battelle/PNL
2:45 PM	Break		
3:00 PM	Lunar Soil Processing & Power Requirements — Processing Methods and Energetics	Brad Cothran	Boeing
3:15 PM	Soil Resources and Processing Concepts	Ben Clark	Martin Marietta
3:30 PM	Open Discussion on Mission Architectures and Implications.	Cmte. at Large	
4:15 PM	Unsolved Questions and Uncertainties: Technology Risk Assessment	Cmte. at Large	
5:00 PM	Adjourn		

TECHNOLOGY WORKSHOP ON LASER BEAMED POWER
MINUTES

Summary

The Technology Workshop on Laser Beamed Power: From Earth to the Moon and Other Applications was held at NASA Lewis Research Center (LeRC) on February 5, 1991. Approximately 50 representatives from NASA Headquarters and research centers, Department of Energy laboratories and private firms participated.

The one-day workshop was arranged by Dr. John Rather of the Space Technology Directorate to assess what role NASA should play in power beaming from the Earth to the moon. The morning presentations focused on optics while the presentations in the afternoon centered on photovoltaics, electric propulsion, and lunar operations. The workshop speakers each had expertise in some aspect of the technology necessary for power beaming, and they generally advocated the development and application of power beaming systems for cis-lunar and lunar applications.

Discussion

Introductory Remarks. Stuart Fordyce, Director of Aerospace Technology at NASA LeRC, was the host for the workshop. LeRC has been designated as the Space Power Center of NASA.

From Earth to the Moon via Laser Beams. John Rather of the Space Technology Directorate, NASA Headquarters, presented a description of the *Segmented Efficient Laser Emission for Non-Nuclear Electricity (SELENE) Program*, a near-to-mid term strategy for powering a lunar base with laser energy from the Earth's surface intended to bootstrap large scale lunar development. The same technologies also make feasible high power operations for satellites and laser electric propulsion vehicles. In the longer term, Dr. Rather suggested that a lunar base might develop the potential to return economic benefit in the form of electric power beamed back to the Earth. Dr. Rather foresees a series of technical experiments and a feasibility demonstration in the 1994-95 time frame followed by an operable system by 1998. Full operation would commence early in the next century. Current work related to SELENE is being achieved through discretionary funding, and program status is planned for 1993.

SELENE includes at least three ground-based stations to permit continuous direct power transmission to the moon. The sites would be located about eight time zones apart, equally distributed about the globe, with two of three sites always having line-of-sight to the moon. Potential sites are Australia, Maui, China Lake, the Canary Islands, Madagascar, Morocco and Chile. Each station would have an induction free electron laser (IFEL) and a 10 m diameter beam director. The Phased Array Mirror Extendable Large Aperture (PAMELA) concept, a proprietary design by Kaman Corporation, is the conceptualized approach for the optical telescope used to project and correct the beam. A power level of up to 10 MW would be transmitted at 0.8 μm and converted to electricity by photovoltaic

arrays to deliver more than 2 MW on the lunar surface, assuming a photovoltaic array conversion efficiency of about 50%. The power reaching the moon would be received over an 80 m diameter area, and the arrays would cover about 5000 m^2 at a cost of less than $0.5 billion.

To reach full SELENE deployment, the feasibility demonstration would show that a near diffraction limited beam could be projected to the moon. The 2.7 kW green laser currently being used by Lawrence Livermore National Laboratory (LLNL) in the isotope separation program is proposed for use, projected by a 10 m structure populated with 2-4 cm PAMELA optics. The cost was estimated at $80 million. Following the initial propagation experiment, he suggested that three 2 MW FEL's be installed at three locations and combined with three 10 m PAMELA telescopes to reach operational capabilities for SELENE. Completion was estimated by 1998 for $2.5 billion for the entire program including the space-based receivers.

The SELENE concept is based on induction linac free electron laser (IFEL) technology. Dr. Rather described an IFEL for SELENE that uses a 150 MeV accelerator employing new cavity designs yielding 2-3 MeV per meter gradients, which could reportedly achieve approximately 20% wallplug efficiency. Referring to Science Research Laboratory (SRL) estimates, he suggested that a 10 MW IFEL might be built for as little as $10-15 million.

Dr. Rather also briefly introduced the concept of laser electric propulsion using the FEL to boost payloads from low Earth orbit (LEO) into low lunar orbit (LLO). He suggested that 3 MW of laser power focused on spacecraft photovoltaic (PV) arrays would boost a 12,000 pound payload from LEO to LLO in 12 days. Although the subject of a later presentation, Dr. Rather seemed to emphasize electric drive as the design of choice for laser propulsion. In passing, he commented that the induction linac FEL could operate at a repetition rate of 20 kHz which would produce AC type power at the spacecraft and minimize the amount of power conditioning required on orbit.

Dr. Rather explained the nature of laser power beaming in the context of other options for lunar power. They included direct solar illumination of PV's with extensive storage on the surface to survive the long lunar nights and on-site nuclear power. His comments dismissed direct solar power from a weight-to-orbit argument based upon the tremendous weight required to store power for 14 days. He similarly dismissed the on-site nuclear option as ruled out for non-technical reasons. That left laser power beaming as the only viable contender until major construction capabilities become feasible on the moon.

Dr. Rather turned to a discussion of atmospheric compensation issues and the role of PAMELA for power beaming. He suggested that lasers situated on three km mountain peaks would be free of many lower atmospheric obscurations and would have a more benign atmosphere through which to propagate. Dr. Rather explained that conventional approaches to atmospheric compensation employed deformable mirrors within the optical train, although this can be expensive. In the early 1970's, he worked at Kitt Peak with a 12 millimeter wave radio-astronomical telescope, and he thought of covering this large mirror with small

adaptive optics components to make it function at short wavelengths. PAMELA grew from this early concepts.

Citing California Institute of Technology work, Dr. Rather said that 10 m diameter precision radio telescopes can be mass produced. In the Caltech design, honeycombed aluminum fastened to a steel frame was cut with a laser controlled mill until a parabolic surface was obtained. Aluminum 2 mm thick was then vacuum bonded to the surface. This process cost $1 million and required three man-years to produce one telescope.

For the PAMELA application, each hexagonal segment would have three actuators for piston, tip and tilt control plus edge sensors coupled to an on-board microchip that senses segment position relative to adjacent segments. The key for success is low-cost high-quality segments. Dr. Rather believes that the cost of the individual segments can be reduced to $200-300 each. One 10 m PAMELA telescope would require 25,000 individual segments and a large back-up structure. If manufacturing is successful, Dr. Rather indicated that the mirror segments would total $5 million and the back-up sheet $1 million for a total of $3 million for the complete telescope.

Control algorithms for this large number of actuated segments may be a problem. Current state-of-the-art is for approximately 25,000 segments, and Dr. Rather believes that 30 iterations at 30 kHz will be required. A two level control system was suggested to keep communication time between segments to a minimum. Finally, the control concept must be scalable and will likely require simple arrays and precision actuators employing heavy parallel processing.

For the near term proof-of-principle experiment proposed for 1994-95, Dr. Rather advocated a 10 m basic telescope structure. His estimates conclude that a 4 m system would cost approximately 75% of the 10 m cost and the scalability added by the larger structure would be worth the expense.

Dr. Rather concluded his introductory remarks and description of SELENE by reminding the audience that this technology was not just for power beaming. In addition, it applies to laser-electric propulsion, life support to manned platforms, and other high power space applications as well as astronomy and intelligence telescopes.

Free Electron Laser Development. Daniel Goodman, Science Research Laboratory (SRL), gave a presentation on *Induction Linac Driven Free Electron Lasers for Beamed Power Applications*, in which he advocated the suitability of induction FEL's for beaming power to the moon.

The highest peak power achieved with an induction linac-driven free electron laser reportedly exceeded 10 GW at a wavelength of 1 cm, and the highest average power possible is anticipated to be greater than 10 MW at the wavelength design value of 1 μm. Efficiency is expected to be less than or equal to 50%. SRL has built a number of 1.5-meter accelerator modules for the FEL; 60 modules are required for the complete system. Common accelerator design issues were identified, and these are expected to be resolved by the end of the first year of the proposed program. These include the output voltage flatness, timing jitter and beam energy spreading.

SRL's program is defined in three phases. Phase I would result in the 1.5 MeV accelerator module fabrication and testing and the wiggler design. In Phase II the beam energy would be extended to 6.5 MeV from the Phase I 1.5 MeV beam energy and wiggler design verification tests would be performed. Phase III would include fabrication of the 50-100 MeV induction accelerator and wiggler. Dates accompanying the phase descriptions show the beginning of Phase I in FY 1991 and completion of Phase III by FY 1995. Funding for this work has come from SDIO, DoE and DoD in the past. SDIO has cancelled their funding in order to support other areas.

Progress in Segmented Mirror Technology. Albert Lazzarini of Kaman Sciences Corporation spoke on *Control Systems for Adaptive Optics Technology.* Kaman recently completed and delivered the adaptive optics package for the Wavefront Control Experiment (WCE), part of the SDIO/AFSSD program Starlab mission. The WCE uses a membrane deformable mirror with 69 actuators, and it was delivered to SDIO in August - September 1990.

Issues affecting the scaling of deformable membrane mirrors to larger apertures include the adaptive control needed in a reduced beam by large aperture collimator/telescope systems and the differences in sensed and controlled spaces. Surface control techniques for large segmented mirrors have been approached through the use of small hexagonal subapertures, as in the PAMELA system. Each segment senses the edge mismatch and corrections are made with pistons. For the described mirror, 25,000 segments are needed. Algorithm convergence performance to find the optimal tilt of the mirror segments with the smallest number of iterations is critical to development.

With regard to laboratory experience, a power level of 1 milliwatt has been used for a mirror with 5 - 7 segments, and several segments have been joined in a dynamic control experiment.

Greg Ames of Kaman Sciences Corporation reported on *Segment Development for SDIO/DARPA.* Phase I of this joint project using the PAMELA technology entailed a six month effort to prove the edge sensing technology of the hexagonal mirrors. Phase II is ongoing and it involves nested control issues for both tilt measurement and piston functions. Phase III will involve the construction of a 36-segment telescope to produce diffraction limited images. A main issue is temperature sensitivity of the segments, and it may be that a trade-off with the dynamic range will be the means to correct it.

SDIO/DARPA Adaptive Optics and Relay Mirror Experiments. Darryl Greenwood of the MIT Lincoln Laboratory discussed *SDIO/DARPA Adaptive Optics and Relay Mirror Experiments.* Dr. Greenwood mentioned Itek, United Technologies and the Air Force Phillips Laboratory as having adaptive optics programs, but he noted that in general the current technology base is very weak.

Three atmospheric phenomena significant to laser propagation and adaptive optics are extinction, atmospheric turbulence and thermal blooming. Turbulence is caused by random heating variations in the atmosphere. Thermal blooming results from the interaction between the beam and the medium, and extinction refers to the losses associated with propagating the beam through the

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atmosphere. Lincoln Lab has an atmospheric compensation program to assess and compensate for the atmospheric effects on laser propagation. This program is currently receiving Army support and has received SDIO funding in the past.

Recent work has been with the ground-based laser at the Air Force Maui site (AMOS) involving the Laser Atmospheric Compensation Experiment (LACE) satellite target. In conjunction with this work, the short wavelength adaptive techniques (SWAT) program uses beacons to compensate for atmospheric turbulence over the laser path.

Dr. Greenwood showed a graph indicating transmission windows in the atmosphere where high power laser beams are best projected. One very good transmission band occurs around 1.06 μm where molecular absorption is very low. A similar transmission window occurs between 0.78 - 0.80 μm, the wavelength of most interest for the SELENE concept. According to several at the workshop, transmission at 0.80 μm provides the best conversion efficiency for gallium arsenide (GaAs) photovoltaic arrays.

Returning to propagation, Dr. Greenwood stated his opinion that even with a fully populated 10 m PAMELA system, some conventional adaptive optics would still be required based upon aerosol absorption. FEL's operating at 1.06 μm have absorption of approximately 0.07%. Several A/O components are operating around the country today. At the Maui test facility one 241 channel, 1 kHz deformable mirror (DM) is being used daily. Another 241 channel DM is operating as a part of the SABLE horizontal path propagation experiment in progress at TRW's Capistrano test site. A third 241 channel mirror is being used at the Lincoln Lab.

In the lexicon of atmospheric propagation, the strehl ratio indicates effectiveness by expressing relative on-axis beam intensity. As an example, Dr. Greenwood showed a sample calculation for a 10 MW laser power beaming FEL operating at 1.06 μm with 0.07% absorption, assuming a 3.5 m telescope with zero slew. Under these conditions, the strehl ratio would be 0.80. If power were increased to 20 MW, the strehl ratio would drop to 0.10. The general scaling rule was $P/d^{1.5}$.

Major components included in a conventional A/O system are the wavefront sensor (WFS), the aperture sharing element (ASE), deformable mirror, fast steering mirror (FSM) and the reconstructor. Dr. Greenwood recommended a 10 cm actuator spacing for the DM and a 10 m conventional beam director for this mission.

Current planning is based on 10 MW exiting from the aperture on the Earth. The following factors will affect the amount of power reaching the moon:

Atmospheric transmission	0.9
Atmospheric compensation	0.5
Collector geometry efficiency	0.9
Array electrical conversion efficiency	0.5

This results in a power level of 2 MW. Power conditioning and waste heat processing reduces power available by 0.8 MW, and therefore the amount available for lunar electrical consumption will be approximately 1 MW. Given the various high energy laser options, Dr. Greenwood advocates the use of the free electron laser because of its tunability, its scalability to high power, the existence of designs for 10 MW, and high potential efficiencies. He believes the a beam control system for efficient transmission of laser power from the Earth to the moon can be built.

Laser Powered Orbital Transfer Vehicles. Grant Logan of the Magnetic Fusion Energy Division, Lawrence Livermore National Laboratory, presented information on *Laser Electric Propulsion: Mission Analysis* in the early afternoon. Specifically he discussed *Laserpath*, a ground-based laser-driven space power and propulsion concept developed several years ago and intended as a manned lunar shuttle vehicle. He believes that the concept has great potential for application of a ground based laser system. In his analysis, he considered 72 round trips between LEO and LLO and included a relay mirror to focus and direct the beam.

Dr. Logan showed estimates of 5 kg/kW for the nuclear option. Given some additional development, he suggested that laser/PV combinations could achieve 0.5 kg/kW. Further, he estimated FEL costs at $5/W. Dr. Logan believes that laser propulsion is economically attractive as an alternative to conventional means.

A laser system has several advantages over solar-powered photovoltaics. The laser permits operation of the photovoltaics at their thermal limit, thus generating more power per unit area. *Laserpath* also exploits the high specific impulse of the plasma thrusters, therefore requiring little propellant mass. Dr. Logan believes that the *Laserpath* concept is worth pursuing in relation to lunar power beaming systems. Dr. Rather later noted that this vehicle, with its large, low weight concentration, may be capable of going from the moon to Mars, and that some interesting questions regarding mission optimization remain yet unexplored.

Dave Byers, Chief of the Low Thrust Propulsion Branch of NASA LeRC, discussed *Beamed Laser Propulsion*. Dr. Byers first outlined the negative aspects of in-space propulsion, which are dominated by the proportionately large prime power mass requirements necessary. Alternately, beamed laser propulsion concepts, both ground and space based, appear attractive for future use. He noted that continuous laser power is not essential, and that pulsed power is effective and sometimes optimal. NASA LeRC has ongoing R&T work in electric propulsion, conjugate/ "nondiffracting" waves and the H_2 rocket.

Electric propulsion concepts are either electrothermal, electrostatic or electromagnetic. Seventy-seven space tests have been conducted in the world in these areas, nearly two-thirds of which have been in the U. S. Low power electric propulsion systems are currently operational.

Problems associated with ground-based lasers for spacecraft propulsion include atmospheric propagation and beam spreading. The approaches taken by LeRC to

alleviate these problems have centered on phase conjugation and "nondiffracting" beams. Theories and experimentation in these areas have an international history over recent decades. Dr. Byers solicited the opinions of the workshop participants as to the application of phase conjugation in adaptive optics. LeRC has an in-house phase conjugation facility operational, including three- and four-wave mixing, a low power HeNe laser and BaTiO3 photorefractive crystals. "Nondiffracting" waves involve solutions to the wave equation which travel without spreading, although it appears that "nondiffracting" waves do diffract. Despite this, LeRC work suggests that certain changes could enhance propagation distances and make the concept more attractive.

Dr. Byers also discussed the H2 laser rocket under development at the University of Illinois. The 10 kW H2 rocket fabrication is nearly complete and testing is planned in Spring 1991. The 100 kW H2 rocket design is complete, and LeRC advocates the fabrication and testing of this larger rocket as well as tests with higher power lasers.

In summary, Dr. Byers stated that mitigation of in-space propulsion penalties requires improvements in performance, potential benefits exist for Earth and planetary propulsion through ground- and space-based lasers, and less than 10 MW is ample for achieving results.

Laser/Photovoltaic (PV) Technology. Geoff Landis of LeRC/Sverdrup, Inc. presented *PV State of the Art Technologies and Implications*. He stressed the following points: the photovoltaic mass should not be considered alone, as the overwhelming majority of solar PV power system mass will be the mass of the energy storage system required for the 354 hour lunar night; electrical conversion efficiency will increase as intensity increases, as long as temperature does not increase too much; and solar flares will result in high energy protons on the moon, which will degrade the photovoltaic cells.

GaAs cells produce the highest energy conversion efficiency. Efficiency is approximately 50% for laser light at intensities of $1 kW/m^2$ near the optimum wavelength of 850 nm. Efficiency drops off rapidly with longer wavelengths and linearly with shorter wavelengths. Both silicon and thin film cells are cheaper but they have lower efficiencies. Current cells are not optimized for laser conversion and have monochromatic conversion efficiency of about 30-40%. To get better efficiency with silicon, Dr. Landis suggested cross-grooving the surface of the cell to increase the exposed surface area per cell and the amount of internal reflection. New materials would be required if wavelengths outside of 600 - 900 nm are necessary.

Dr. Landis stated that the life expectancy of the cells on the lunar surface would only be influenced by environmental anomalies, such as solar flare activity, which would cause a 5% degradation in the cell for each occurrence. He also seemed to state that no degradation would occur inherently in the cell, and that laser drift would not affect the cells. Cell degradation has always been a major concern of PV developers. John Rather pointed out that indium phosphide cells under development at the Naval Research Laboratory are self annealing and retain their efficiency at the 90% level after heavy exposure to particle radiation.

In a comparison of the weight required for a laser powered PV system versus a power storage system on the moon in order to show the tremendous savings with the former, Dr. Landis presented tables of weight estimates for detector arrays and the corresponding weight for lunar power storage. He said that lasers can cut requirements to 1/30 of current technology requirements. These are summarized below.

Photovoltaic Technologies:

Present	1250 kg
Next Generation	540 kg
Advanced	360 kg

Storage Technologies:

Ni-H batteries	2,400,000 kg
Regenerative fuel cells, conventional	110,000 kg
Regenerative fuel cells, cryogenic	20,240 kg

Ed Coomes of the Pacific Northwest Laboratory/Battelle Memorial Institute spoke on the *Laser/PV Qualification Experiment*. He indicated that he was particularly advocating nuclear or solar power beaming, and especially space-to-space power. He would like to see space power generation and distribution parallel to terrestrial power systems.

His expression of the advantages of power beaming included the commonality of power assets, technology synergism, nuclear systems in high Earth orbit to create increased safety, power availability increased by an order of magnitude, new civilian and military options available, and the power infrastructure available for space commercialization. He indicated that power beaming would be useful for orbital transition.

Mr. Coomes said that laser conversion efficiency was 10 times that of solar. He estimated conversion efficiency of GaAs around 50% at 25 °C. By altering cell dimensions, he believes efficiency would reach 60%. He further stated that 70% efficiency may be possible with a dopant in the GaAs. He is currently working with Dr. Olsen at the University of Washington to investigate these theories.

Lunar Soil Processing and Power Requirements. Representatives of Boeing discussed *Processing Methods and Energetics*. Brent Sherwood of Boeing gave an overview of Boeing's end-to-end systems study of lunar power and processing. The plan includes the reduction of lunar ilmenite to result in 100 tons of oxygen per year, and the use of regenerative fuel cells. Power would be needed for survival as well as light industrial processes. The following power demands were suggested.

Early lunar activity	20 kWe
Continuous power for habitat and science	100 kWe
Early oxygen prod'n/pilot fabrication plant	1 MWe
Early fabrication industrial production	5 MWe
Growth of resource production base	10-100 MWe
Subsurface habitation tunnel melting	500 MW thermal

Brad Cothran, also of Boeing, reviewed research of several decades ago in which space power technologies were evaluated. The free electron laser was in its infancy, but it looked promising due to its tunability and its light weight. Ben Clark of Martin Marietta discussed *Soil Resources and Processing Concepts*. He outlined Martin Marietta's lunar evolution case study, which did not rely upon laser power.

General Discussion. A general discussion followed, in which Dr. Rather queried everyone's overall impressions. He reiterated that power beaming is a means to bootstrap lunar development, and that power beaming would only be required for 10 - 15 years while operations on the moon are becoming self-sufficient. Dr. Rather stated that with three ground sites, the probability of power outage on the moon would be 1:100. With six ground sites, the probability decreased to 1:10,000.

He noted that the big picture must be studied with regard to power beaming and that alternate approaches must be considered. Power beaming has been viewed negatively due to its ties to two outlandish schemes in the past. The present intent is to determine what aspects of power beaming can be made to happen first, so that the final goal can be achieved through incremental steps. Dr. Byers added that they must also consider applications in Earth orbit for the near term, and that kW power systems offer promise. Dr. Rather added that today's discussions were not meant to be exclusively lunar. Relay mirror systems were briefly discussed.

Dr. Rather believes that the joining of silicon microelectronics and large scale optics is a worthwhile technical challenge, and he urged the participants to give serious consideration to the concepts discussed today to help move this program forward.

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TECHNOLOGY WORKSHOP ON LASER BEAMED POWER
From Earth to the Moon and other Applications
NASA LEWIS RESEARCH CENTER
Cleveland, Ohio
February 5, 1991

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Project "SELENE"

An innovative, low-cost solution to the need for large amounts
of electrical power for lunar development.

An efficient, low cost method for transportation in cis-lunar
space.

A non-nuclear method for providing high power for radar
satellites and direct broadcast satellites

by

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November 1990

DISCLAIMER

The following text is Dr. John Rather's original conception of the SELENE program. The SELENE program is still evolving, and this is provided to stimulate the reader's thoughts concerning the ultimate possibilities of the concept and programmatic issues.

ABSTRACT

We propose a three year project to develop technologies for and demonstrate the feasibility of laser power beaming to the moon. The feasibility demonstration will involve developing a revolutionary new beam expander optical system using a highly segmented phased array primary reflector to compensate for atmospheric, structural, and tracking perturbations. This beam expander will be coupled to a readily available 2 kilowatt copper vapor laser module (or similar laser) to deliver power to the Apollo retro-reflectors now on the moon. Photometry of the returned signal will indicate the degree of success of concentrating and stabilizing a diffraction-limited spot on the moon, which is tantamount to demonstrating the ability to beam large amounts of power to the moon or to any point in cislunar space.

Since the lunar night is two weeks long, there is a critical need for power at any permanent manned installation. It can be shown that as few as three laser sites spaced 120° apart around the earth can ultimately satisfy the need for continuous megawatts of power on the moon at a small fraction of the cost of any other method. (The astronauts will merely have to unroll high efficiency laser photovoltaic cells over an area about 80 meters in diameter on the moon's surface and emplace a small laser beacon beside the array.) Synergistically, the system would also make feasible laser electric propulsion for efficient transfer of large masses from low earth orbit to low lunar orbit. Other applications include supplying large amounts of reliable power to high power radars and other transmitters in high or low orbits. The presently proposed demonstration will prove the feasibility of the most difficult aspects of these concepts.

Implicit in this program is the development of a totally new approach to large scale adaptive optics and telescope design which has the potential to cut the cost and fabrication time for large optics by a factor of ten. At the same time, this approach will render feasible the construction of low weight telescopes and beam expanders both on earth and in space having apertures much larger than any previously achievable (>15 meters at optical wavelengths). These capabilities will greatly enhance and facilitate optical system design for space, defense, intelligence, and astronomy.

The program has been named project SELENE, after the ancient Greek goddess of the moon. The acronym means "Segmented Efficient Laser Emission for Non- nuclear Electricity".

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BACKGROUND

Although the optical sciences have made enormous progress in the past three decades, the fabrication times and costs of large optical apertures for telescopes and laser beam expanders remain very large. Despite major US research activities such as the Strategic Defense Initiative's Rapid Optics Fabrication Technologies (ROFT) effort, breakthroughs have not occurred which are necessary to make feasible large, inexpensive, lightweight, rugged, deployable, and fully adaptive, telescope systems to achieve diffraction-limited performance at visible wavelengths either on the ground or in space. Many critical technological shortfalls also remain in adaptive optics research. In particular, deformable mirrors and wavefront reconstructors required in typical adaptive optical systems are complex and expensive. The work proposed here addresses important technological deficits in all past and present programs. Successful completion of the proposed work will not only make a major new contribution to the United States space program that is highly appropriate in the context of NASA's response to the Augustine Panel recommendations, but also will open new capabilities for economical high performance power generation, propulsion, optical data transmission, surveillance systems, and astronomy. Appendix 1 provides some details of the application which is the immediate focus of the present proposal, namely the use of such an adaptive optical system to transmit large amounts of power.

The work proposed is based upon an extensive knowledge base developed over two decades in numerous laboratories and private companies (see Appendix 2). In particular, before his recent affiliation with NASA, the present author led a five year effort at Kaman Corporation to exploit new approaches to adaptive optics as a means for achieving superior optical system performance. First, he created the Strategic Defense Initiative Organization's STARLAB concept to achieve and demonstrate weapons grade laser pointing and tracking using adaptive optics in the so-called Wavefront Control Experiment (WCE). He also invented and patented Kaman's PAMELA concept, an acronym meaning "Phased Array Mirror, Extendible Large Aperture", which points the way to the presently proposed work. Appendix 3 outlines the PAMELA adaptive optics concept.

While the fundamental feasibility of a specific phased array segmented optics approach has been verified by Kaman Corporation under a contract with the Strategic Defense Initiative Organization (SDIO), a large amount of work remains to be done that is appropriate to the capabilities of

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government laboratories and private industry. Alternate concepts may also benefit from a diversity of expertise. In order to bring the best technology to maturity in minimum time, we propose to initiate innovative adaptive optics work immediately under a joint program between NASA and SDIO. Efforts are already in progress to initiate joint funding to carry the work to logical large scale applications. The NASA power beaming effort is the first such proposed research partnership.

In order for the proposed concept for laser power beaming to figure in NASA's planning for the Space Exploration Initiative and other NASA and Department of Defense planning, it is essential that the proposed feasibility demonstration be carried out at flank speed. Hence, the proposed program is structured to accomplish the full demonstration by the end of FY95. This entails carefully planned parallel programs beginning in FY92, leading to production of critical subsystems such as adaptive optical segments, control algorithms, wavefront sensor components, the telescope/beam expander structure, the required reference "guidestar", the laser itself, and the site selection and planning. We thus propose an aggressive effort beginning with modest funding in the present FY1991 in which discretionary funds accomplish the required initial planning and designs and the expected out-year funding can then be used immediately to launch the time-constrained hardware work. Significant involvements of private industry will also be necessary, with increasing roles later in the program.

For the future, there are many important ramifications of the proposed work. In connection with the Augustine Panel recommendations, NASA will have established a direct, long-term response to the call for new, innovative technologies expressed in recommendation #8. Moreover, NASA can logically proceed to development of a robust electric propulsion system, a laser photovoltaic power array for the lunar surface, and technologies for utilizing and processing lunar materials. The 16 meter astronomical telescope for the lunar surface now in the initial study phase at NASA will also be very favorably impacted by the new optical technologies. In other areas, this same technology will lead to many other future Government programs for defense, intelligence, and numerous scientific purposes.

GOALS AND PERFORMANCE

Overall, the research goals can be summarized: Review multi-element adaptive optical systems, choose the best candidate for intensive development, and then develop the materials, fabrication methods wavefront sensing, optical element actuation and control technolo..

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necessary to realize the benefits of highly segmented adaptive optics. Engineer the required support structure for a ground based demonstration telescope/laser beam expander. With appropriate industrial partners, produce a telescope/laser beam expander and perform an experiment to demonstrate near-diffraction-limited power transmission to the moon. Plan for future defense and intelligence space applications.

Cost effective work can take place because the project, as proposed, is large enough to have a critical mass and because team members from within and outside NASA can complement each other's support. Figure 1 outlines the overall costs and provides a basic time line for each major phase of the project. Note that the success of the program depends upon a well structured parallel effort from the inception. Between 10 and 12 full-time equivalent personnel, organized as illustrated in Figure 2, will be required for launching the project during the first year. Most of the required support will be science and engineering from several scientific disciplines. During the second and following years, major fabrication and machine shop support will be required to construct test articles. Projected growth in outside funding in the second and following years will greatly expand the number of people supported at NASA Centers and in external teaming organizations.

As indicated in Figure 1, the logical objectives of the work reside in six areas:

(1) Industrialize the Optical Segments and Wavefront Control System: Thus far, Kaman Corp. has realized only one "hand-forged" design using inductive edge sensors and electromagnetic actuators to control molded silicon carbide segments. It is highly likely that advanced chemistry and engineering methods can design and arrange to produce a more optimum design suitable for low cost mass production. This is an essential, central need that must be satisfied, therefore it insures participation by a variety of skilled NASA and outside supporting people. The closely coupled sensing and control hardware leading to a workable overall system must be designed to preserve the economies and scalability of the concept.
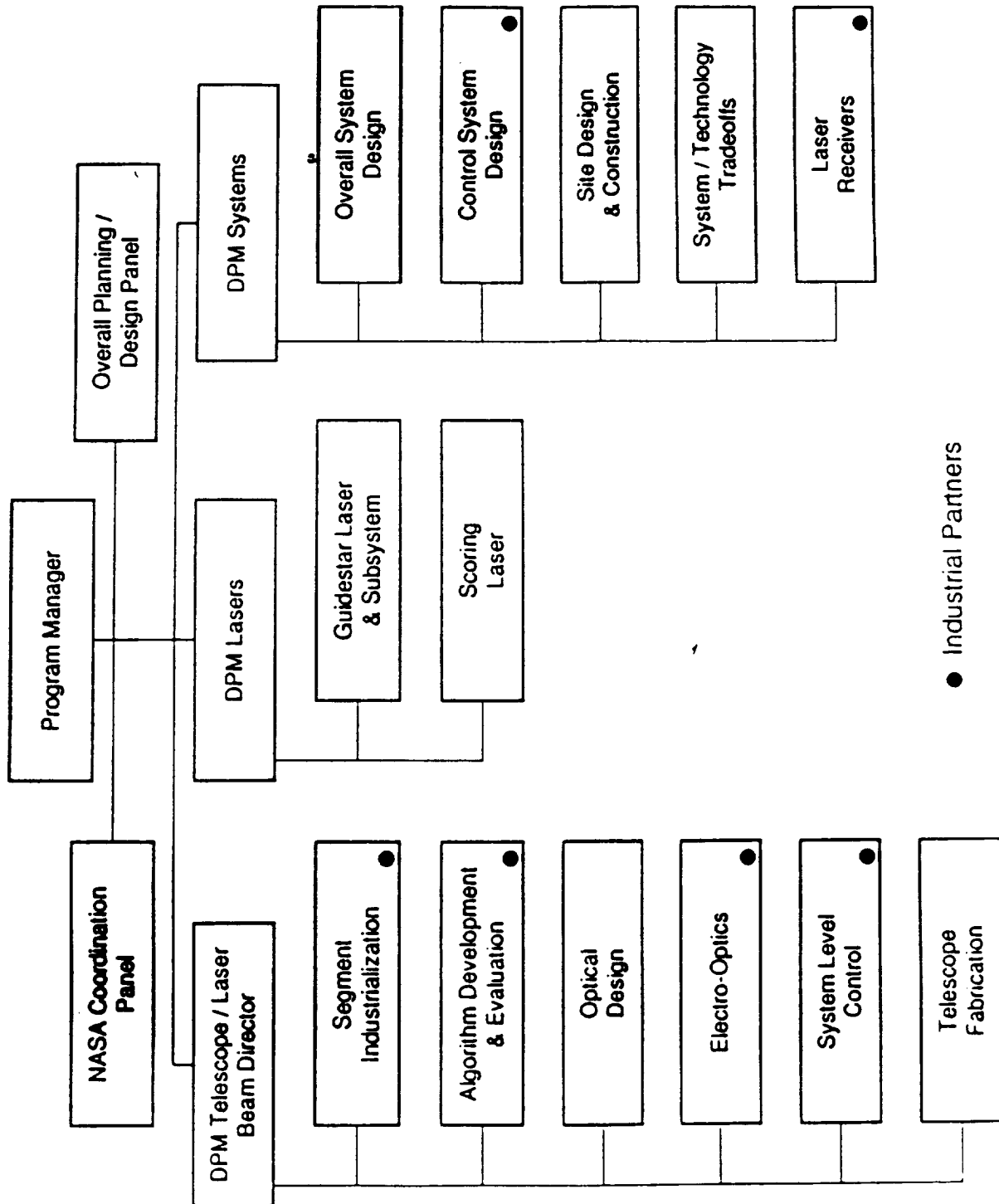
(2) Prove the Algorithms: Sophisticated control is a principal key to success in highly segmented optics. Kaman Corp., Thermo-Technologies, Corp. and the M.I.T. Lincoln Laboratory have partially tested and verified various approaches to the control of thousands of adaptive elements. (The approach used by Kaman was initially based upon neural network ideas borrowed from Los Alamos National Laboratory and innovated upon by FORTH, Inc..) The mathematical and computing resources available with a well funded. coordinated effort will bring a new dimension to the work which should lead

NASA

Project SELENE* : Major Activities and Costs

* Segmented Efficient Laser Emission for Non-nuclear Electricity

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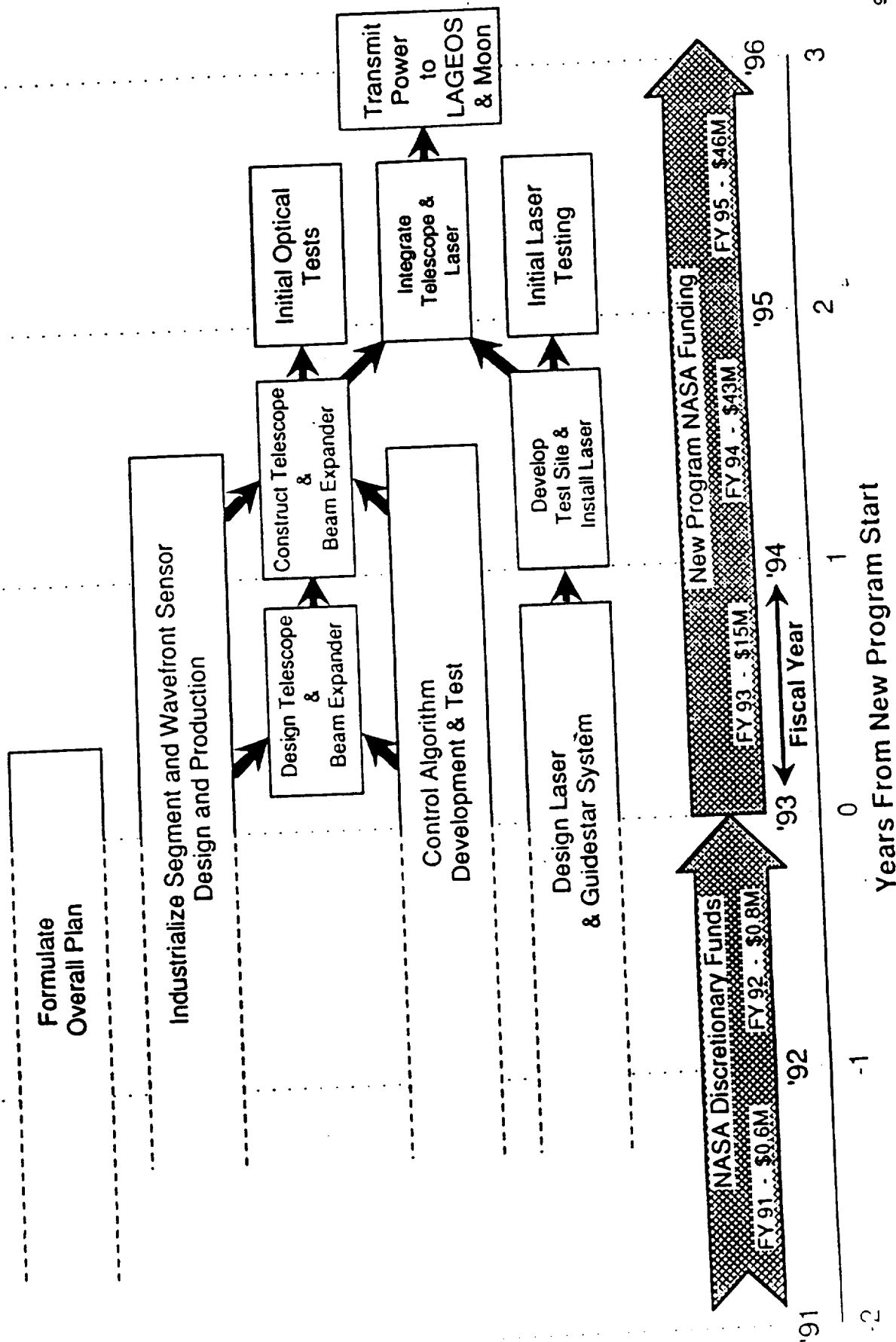
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System Level Control ●

Telescope Fabrication

Guidestar Laser & Subsystem

Scoring Laser

Overall System Design

Control System Design ●

Site Design & Construction

System / Technology Tradeoffs

Laser Receivers ●

● Industrial Partners

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to better, faster, more scalable algorithms. System simulation is vital to prove success before labor intensive fabrication is begun.

(3) <u>Design a Complete System:</u> End-to-end system design will entail optimization of all the subsystems. This activity has a scope appropriate to particular talents of laser physicists and engineers at NASA Centers and outside entities. A particularly interesting and important part of the problem is how to obtain the needed information to enable the necessary adaptive control of the surface. Part of the information can be locally sensed. Both edge-match and surface figure can be locally measured and controlled, but full correction for external wavefront perturbations (such as atmospheric effects) will require ample external photons. These photons can be obtained in a variety of ways, but the challenge is to find the simplest and least expensive wavefront sensing approach. This will be discussed below in Appendix 4 with reference to unresolved issues.

(4) <u>Build a Telescope:</u> The Keck Foundation is already expressing interest in building a second ten-meter diameter telescope on Mauna Kea, the new one having some adaptive optics capabilities. (NASA has already signed a Memorandum of Understanding with the Keck foundation regarding participation.) This will be exceedingly expensive and difficult if existing methods are used. An innovative telescope of the proposed new design will be much easier to realize, much less expensive, and could have an aperture larger than ten meters. To prove this, however, we will have to build a real telescope in the near term. It is reasonable for NASA to undertake building a three or four meter diameter telescope/laser beam expander to demonstrate end-to-end feasibility in three years. (In fact, we believe that a much larger structure - at least ten meters in diameter- can be built directly at low cost and only partially filled with adaptive segments to achieve the necessary demonstration. Upon achieving a successful demonstration, the system can then be easily and economically scaled to full aperture performance.) The Keck Foundation should be persuaded to support the astronomy-related part of this work. If success is achieved, a sixteen meter diameter state-of-the-art telescope can likely be built within another three years that will change the future of astronomy forever, while also making NASA a world class player in several new critical areas. Moreover, this telescope will serve as an Earth-based prototype for the sixteen meter telescope that NASA is now contemplating for the lunar base.

(5) <u>Integrate Telescope and Laser:</u> An important aspect of the external funded support now being sought is to demonstrate practical power beaming from the Earth to space for NASA applications. This is described in more detail in Appendix 1. If the telescope described in (4) above is properly

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conceived and designed, it can serve as an early testbed for efficient power beaming. We propose to integrate a laser (possibly one of the copper vapor/dye lasers built at the Lawrence Livermore National Laboratory for laser isotope separation) with the telescope to demonstrate successful transfer of power with full atmospheric phase conjugation. In parallel with this effort, NASA will also pursue high power laser development as described below.

(6) Do Technology Development Leading to Low-Cost FEL: The high-power beaming system will be compellingly cost-effective if improvements in Free Electron Laser Technology now on the drawing board are realized. SDIO has funded development of one module of the required accelerator. Enough modules must be built to verify that the electron beam quality is scaling as required to yield the performance predicted by analytical calculations.

Some industrial base exists both for NASA to draw on and to team with (as well as for generation of appropriate technology transfer activities) in order to achieve the long term, large scale defense, space, intelligence, and astronomical applications. No integrated systems level effort now exists, however, to achieve each of the necessary steps to realize the full theoretical benefits of large segmented phased arrays coupled with high power Free Electron Lasers. Development and engineering of economical mass production techniques for the fabrication of optical segments, sensors and controls is necessary for practical applications. Moreover, development of the theory and practice of large, extremely low weight, anti-resonant structures is essential for full exploitation of the related applications and missions. This proposal addresses all of these needs and will lead to important optical breakthroughs in a carefully staged, success-oriented program.

Table 1 lists the principal tasks to be performed in the first year and the orientation of the NASA leadership. Apportionment of the full $15 million required to effect the fast track program is also indicated in Table 1. The additional $1.4 million of FY1991 and FY1992 "seed money" will be used for start-up activities in each category pending availability of the bulk of the funding. These start-up activities include detailed concept formulation and evaluation, prioritization of technology action items, production of working drawings, site selection, and investigation of environmental issues. The overall first year effort will lead to laboratory test articles for the end-to-end beam expander system at the modular level plus detailed plans and designs for the entire program. Figure 3 provides further details of the programmatic focus and management responsibilities for the entire three year effort.

Table 1: Project SELENE First Fully Funded Year Tasks and Costs

Task I. Evaluation of Utility of Laser Power Beaming: $1.5M
- o Use of watts via laser rather than transported power units
- o Laser/electric propulsion system (LEPS) mission analysis
- o Laser power based Lunar colony mission analysis
- o Laser power roles for Mars mission
- o Cost/value comparison

Task II. SELENE Experiment System Design; $3.5M
- o Relationship between SELENE Experiment and operational system
- o System tradeoffs: wavelength, aperture, laser type, etc.
- o Overall experiment plan: Guidestar (?), etc.
- o Risk evaluation and reduction as necessary
- o Experiment development plan: site, laser, laser beam director, adaptive optics
- o Site design and permit applications

Task III. Laser Beam Director and Adaptive Optics ; $9.0M
- o System level: overall concept selection
- o Sub-system level: wavefront control, beam train, telescope, C3, site
- o Segment producibility development
- o Critical components: wavefront sensor, wavefront corrector, adaptive optics control hardware, hybrid circuit development
- o Computer architecture and software system development
- o Control algorithm development
- o Detailed development plans and working drawings

Task IV. Long Term Plan and SYstems Development: $1.0M
- o Development plans for:
  - High energy lasers
  - Photovoltaic receivers
  - Earth sites
  - Electric propulsion systems
  - Lunar sites

Total $15.0M
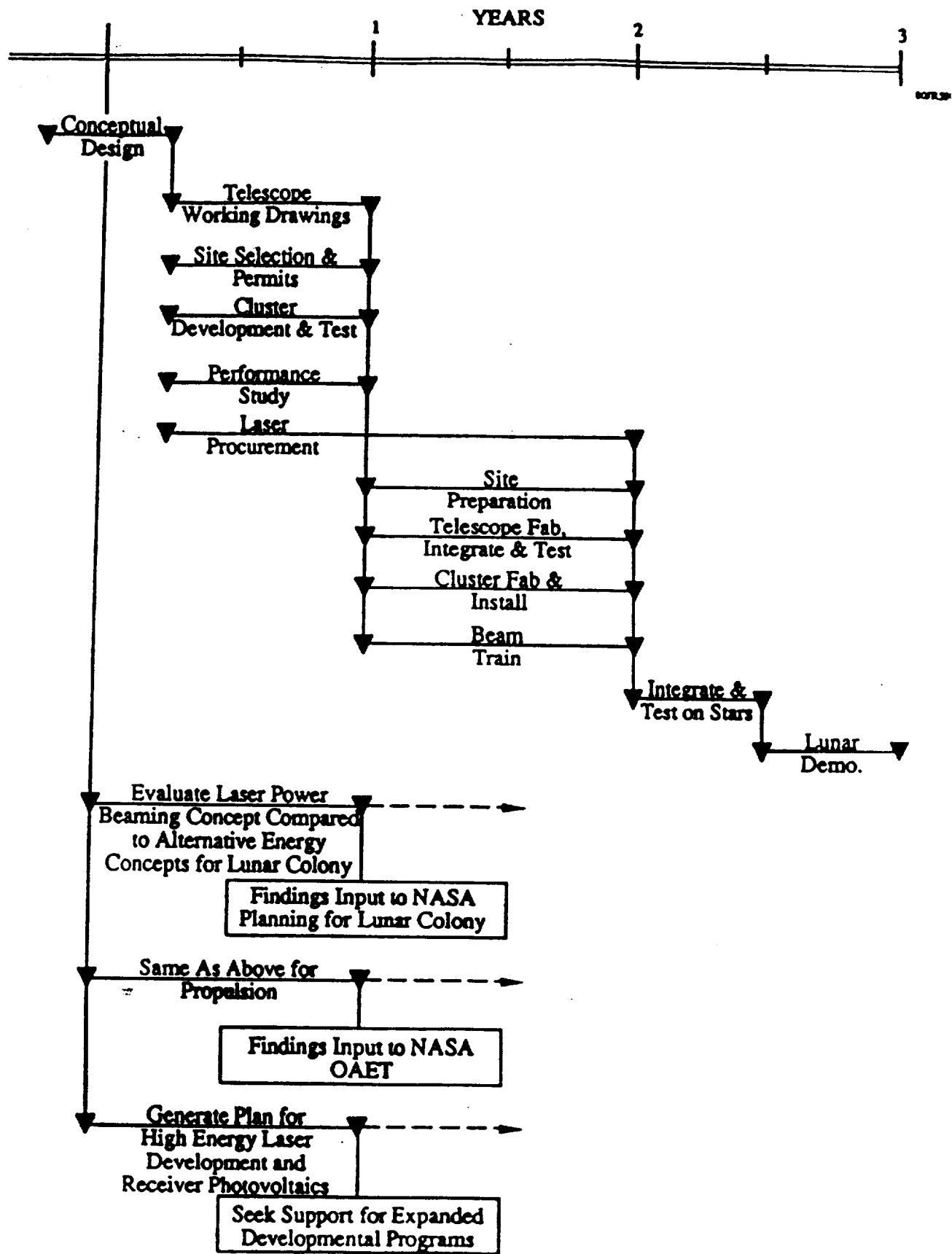
Figure 3.

SELENE PROGRAMMATIC DETAILS

When on the moon, the early outpost developers face the serious problem of obtaining power during the two week long lunar night. Solar power can and will play a major role, but it is itself insufficient, at least until a circum-lunar power grid can be established. Nuclear power is technically feasible, but it appears to be extremely expensive and would engender major safety and environmental concerns. Because the moon keeps the same side facing the earth at all times, however, a real possibility exists for a laser power beaming strategy which will send power to the moon by using ground based lasers on the earth. This can be both very cost-effective and also technically feasible and implementable during this decade because most of the capital equipment remains on the earth, uses earth-based resources, and does not have to be "space rated." Since the mean earth-moon distance is about 384,000 Km, a 10 meter diameter projector aperture with a laser wavelength of 0.8 micron would project a spot on the moon only 80 m in diameter if near diffraction-limited performance can be achieved. The illuminated area (5000 m2) is small enough for the astronauts easily to unroll photovoltaic cells directly on the lunar surface. For 10 MW of laser power transmitted and 30% conversion efficiency on the moon (already demonstrated for laser excited photovoltaic cells at 0.8 micron), 3MW of power would be delivered to the lunar base. The power density impinging on the array would be about 2 kW/m2, or roughly twice solar. Array cooling would be passive. An astronaut could walk through the beam and survive, and a special filter built into all spacesuit helmets would protect eyes from scattered (invisible) infrared laser radiation.

Since the earth's atmosphere distorts the upward propagating beam, some form of adaptive compensation will be essential. If one places a small telescope with a low power pilot laser adjacent to the array on the moon, the returned beam sensed on the Earth would provide the phase conjugate reference for correcting the outgoing power transmission beam. This system is then termed "cooperative", unlike the "uncooperative" targets of the military, and the required performance will be much easier to achieve. Further, this "essential reference beam" approach makes safety easily accomplished on Eart because any aircraft that begins to penetrate the outer diffraction pattern wi be detected early enough by a simple radar system to turn off the high powe laser. (The reference signal can be cut off and the laser pulser stopped withi a millisecond.) Non-linear atmospheric propagation problems such as therma blooming are not expected to be significant because of the large aperture of th transmitter and the relatively low power level compared with laser weapo needs.

A-13

In addition to powering the lunar base, such a system could also delive megawatts to a small, efficient photovoltaic array for electric propulsion fror Low Earth Orbit (LEO) to Low Lunar Orbit (LLO) or partway to Mars. Three grour stations on Earth would be required, located eight time zones apart. Two woui. be within sight of the moon at any time, and the third would be available fc propulsion missions.

To prove feasibility of this concept, an impressive short teri demonstration is the central focus of the proposed joint effort of NASA wit DoD and Industry. The experimental telescope/beam expander described abov will be integrated with a kilowatt-class laser to demonstrate effectiv(diffraction-limited power transmission to the retro-reflectors at the Apoll sites on the moon and to the LAGEOS geodetic satellite. The experiment may t located at an existing NASA site or it may be desirable to find a bette location.

The technical parameters of the experiment are summarized in Figure 4. can be seen that the power levels to sustain full adaptive correction fr atmospheric disturbances are reasonable using only the return from the lun retro-reflectors. Interestingly, the required laser power actually decreases ; the aperture size increases because the illuminated area on the moon smaller and the return signal is proportionately brighter. A possib complication is discussed below in Appendix 4.

When the beam is successfully coalesced on the retro-reflectors, the retu wave will be easily visible in binoculars. It will appear as a 4th magnitude gc star within the horns of the crescent moon. This will draw world-wide intere and will clearly establish technology innovation as a major factor in the L space program.

- ## Number of photocounts per sub-aperture per frame

$$N_{sa} = \left(\frac{J_o \sigma_{cc}}{(1.2 \lambda R/D)^2}\right) \left(\frac{T^2 E^2 \eta}{h\nu}\right) \left(\frac{r_o}{R}\right)^2$$

- ## Parameters used for calculations:

Symbol	Definition	Value
N_{sa}	Photocount per sub-aperture per frame	10^3
J_o	joules per pulse	
η	quantum efficiency	0.8
D	transmitter aperture diameter	
T	transmittance of atmosphere	0.8
$h\nu$	photon energy	2.5×10^{-19} J
E	transmittance of optics	0.8
R	range to moon	4×10^8 m
r_o	atmospheric coherence length at 0.8 μm	0.1 m
PRF	pulse repetition frequency	10^3/sec
λ	wavelength	0.8 μm
σ_{cc}	corner cube cross section	$1.7 \times 10^8 \frac{m^2}{SR}$
PAV	$(J_o)(PRF)$	

- ## Average power required for various aperture diameters

D	$\left(\dfrac{D}{r_o}\right)^2$	P_{av}
2m	400	2.7Kw
3m	900	1.2Kw
4m	1,600	680w

Appendix 1: ALTERNATIVE SPACE POWER, A CRUCIAL PROGRAM

National priorities now evolving call for establishing permanent outp on the moon, hopefully during the next decade. The moon will then serve ι base for science and engineering supporting further explorations to Mars beyond. Astronomical observatories on the moon will provide for observat not readily obtainable from earth orbit. Plans call for astronauts to engag mining operations and, eventually, to fabricate many of their basic mate and space exploration fuels on the moon itself. All of this will be expen: and the technical challenge is not just one of putting humankind on the n again, but of putting people there in abundance and at affordable cost. ¯ major technical challenges lie ahead in finding innovative methods implement this national goal. Central to all of this is Energy: Energy propulsion; Energy for building the outposts; Energy for support of activities on the lunar surface and in cislunar space. A major energy-inter problem requiring early attention will be dealing with the highly abrasive l dust, which will be scattered over large areas by each rocket landing takeoff. This will necessitate preparing a landing area early in the histor the outpost, probably by removing the dust over a large area to bedrock (ι 10 meters below the surface). Such a major operation will require electric dozers with considerable power. Intelligent planning also calls for recove useful hydrogen, oxygen and nitrogen from the dust at the same time, since dust must be processed anyway.

The first workable Adaptive Optics (AO) concept was demonstrated b
Hughes Research Lab in 1971. The supporting technologies evolved rapidly i
the 1970s to develop the DARPA satellite imaging activity atop Mt. Haleakal
on Maui (which became known as "AMOS" for ARPA Maui Observing Station
Major players in this work were the MIT Lincoln Laboratory, Lockheed, Itek, ar
United Technologies. Subsequently in the 1980s, the AMOS site was chosen fc
DARPA/Lincoln Lab/SDIO experiments to prove the feasibility of ground t
space and relay mirror laser transmission with nearly perfect correction fc
atmospheric distortions. Some notable progenitors and effecters of thes
highly successful programs were Edward T. Gerry, Darryl Greenwood, ar
Joseph Mangano. Hundreds of technical papers describing this work exist in th
classified and unclassified literature.

While the above programs advanced the adaptive optics art greatly, the
engendered only limited technology innovations. Itek continued to devel
deformable mirrors (DM) to be used at tertiary (or subsequent) locations in tl
optical trains of telescopes. Itek increased the number of DM controllab
zones to several hundred while also trying to scale up the shearii
interferometer wavefront sensor used by Itek in the AO control loc
Meanwhile, Adaptive Optics Associates (now owned by United Technologie
developed innovative wavefront sensors based upon the Shack-Hartma
tilt-sensing principle. Because of the large technical difficulties, freque
equipment failures, and high costs of these approaches, N. (Bert) Massie beg
to experiment at Rocketdyne, Inc. in the early 1980s with segmented mirrors
replace deformable mirrors. Subsequently he transferred to Western Resea
(now Thermo-Technologies, Inc.), where he made major contributions to t
development of segmented mirrors containing up to 500 segments. The
mirrors were intended for location at a tertiary position in a high pov
excimer laser system that was never completed. Massie is now at LLNL and t
been involved in the conceptualization of the present proposal.

Meanwhile, the art of building large optical telescope mirrors v
developed by Perkin-Elmer, Kodak, and other companies in the 60s and 70s
space applications including the Hubble Space Telescope. Six surplus mirr
were integrated by the Smithsonian Astrophysical Observatory to build
Multiple Mirror Telescope on Mt. Hopkins in Arizona. A very large sp
intelligence telescope called HALO was the subject of extensive research
was never built because of prohibitive costs and technical shortfalls. Ro
Angel at the University of Arizona has extended light weight mirror cas
techniques to the present reach toward eight meter state-of-the-art
monolithic mirrors. Jerry Nelson at Berkeley inspired the ten meter K

telescope now nearing completion on Mauna Kea, Hawaii. The latter telescope primary aperture consists of 36 aspherical hexagonal segments ~1.8 meters across which are edge-matched by edge sensors and motorized micrometer screws. This system corrects only for gravitational and thermal distortions and does not adapt for the atmosphere. The aspherical Keck mirrors have been made with great difficulty by Itek and Tinsley, Inc. Both the large monolithic mirrors and the Keck-type multi-segmented apertures are still quite expensive to integrate into a full telescope system (~$100 million without atmospheric-correcting adaptive optical capabilities).

Attempts to build large adaptive deformable primary mirrors have been remarkably slow coming. For over a decade Lockheed, Itek and other subcontractors developed the LAMP mirror, conceived primarily for 2.7 micron wavelength chemical lasers in space. Seven large segments about 2 cm thick were integrated with actuators spaced at ~15 cm intervals to form a 4 meter aperture. While such systems have been proven feasible, they are extremely expensive. A much more economical 3 meter telescope has been built by astronomers with the name New Technology Telescope. The latter instrument became operable in 1989 and is returning excellent results, but still does not correct for atmospheric disturbances.

The other crucial component of a fully adaptive telescope system capable of correcting for atmospheric disturbances is the reference wave system. If the target under observation is not bright enough to supply the needed photons to sense wavefront disturbances, an artificial "star" must be created by using laser backscatter from the upper atmosphere. DARPA, the USAF, and SDIO have conducted numerous experiments to develop this technique under highly classified programs. In the past three years astronomers in France and at the University of Hawaii have been developing similar techniques for astronomic telescopes. Interestingly, Tom Karr, formerly of Lockheed and now at LLNL wrote a concept study in 1986 that suggested using lunar retro- reflectors for an adaptive optics experiment.

A thorough knowledge of this historical background underlies the PAMELA adaptive primary aperture approach conceived by John Rather. PAMELA will be described in more detail below in Appendix 3. After several attempts, a workable concept was formulated in 1986 by Rather, et al at Kaman Corporation. Government supported IR&D was followed by a small technology development contract with SDIO which is on-going at Kaman.

The presently proposed program seeks to build upon all of this previous knowledge base to achieve bigger and better overall telescope systems that can be achieved more quickly and at substantially reduced cost.

A-18

Appendix 3: SEGMENTED OPTICS

To implement the large low-cost primary and the adaptive optics, we advocate the use of highly segmented mirror primaries for which the segments are small enough so that they are also the adaptive element for phase compensation. When a mirror is made from small segments, several substantial advantages are obtained. As the diameter of the segments decreases, they can become thinner, lighter, and more agile. Thermal distortions are reduced by the ratio of the diameter of the segment to the diameter of the primary. At the same time, "mirror seeing" distortions are eliminated because the small segments quickly reach thermal equilibrium with their environment and thus do not engender local convection. Calculations suggest that no active cooling would be required, even for 6 kW/cm2 power density, with a substantial reduction in cost and maintenance. Also, the mirror can be easily repaired. Should any contaminating particles be on the surface during high laser power operation, catastrophic surface failure of a monolithic mirror would result. In a highly segmented array the damaged segment could be pulled and replaced at a very small cost. If a typical solid contiguous primary, a multi-million dollar item, were used and damaged, repair would be very expensive in cost and down time. Small mirror segments can be heated during vacuum coating, and this allows the application of high performance optical coatings. (Coating a large monolithic primary at all would be difficult and extremely expensive.) Since in a highly segmented system the segments are light, the weight, cost, and performance of the support structure are improved. All of these advantages will be realized in the NASA SELENE program.

PAMELA is now the subject of a small (~$2.5 million) SDIO technolog development contract with Kaman Corporation to prove feasibility of the basic concept. While this work is proceeding well from the technical standpoint, does not have the resources to realize its full potential. Defense and civilia applications exist for adaptive optical technologies that are beyond the scop and objectives of present SDIO funded research. The presently propose program aims to build upon previous work and extend it substantially.

For reference, Figure 5 shows the basic PAMELA concept. Small, essential identical hexagonal mirror segments are to be mass produced at low cost. Eac segment is a precision machine having (1) edge sensors capable of measurin edge-match of adjacent segments to ~10 nm rms across a gap of ~100μm. (three long-stroke actuators capable of moving the segment ±100 μm in strok and jointly providing segment tilt to a precision of ,V100 nrad rms. and (

microprocessor electronics to combine the local contrc. signals from the edge sensors with global control signals provided from a wavelength sensor via optical fibers to compute the drive control signals for the actuators. Since the segments are small, lightweight, and agile, they car ntinuously move to the required positions to conjugate continuous phase disturbances caused either by the atmosphere or by mechanical disturbances to the telescope structure Because of the very small gaps between segments, th-a diffraction pattern has been shown to be quite adequate for critical laser a d imaging applications The microprocessors for the ensemble of segments work together as a massive parallel processor, eliminating the need for the costly and expensive wavefron reconstructors now employed in conventional adaptive optics telescope systems. The control loop can be closed at >1 kHz, permitting corrections fo all disturbances and allowing the surface to behave as a very low inertia continuous membrane.

Because a PAMELA-type telescope structure and its large primary reflecto can be lightweight and composed of mass-produced identical items, it can be shown that a ground-based twelve meter diameter filled aperture telescop capable of near diffraction-limited performance may be realizable for unde $50 million, a factor of ten reduction in cost from present technology. Th specific mass of space-based multi-segmented telescope primary reflectc (including support cell) for optical wavelengths is expected to be ~25 kg/m; also a factor of ten improvement.
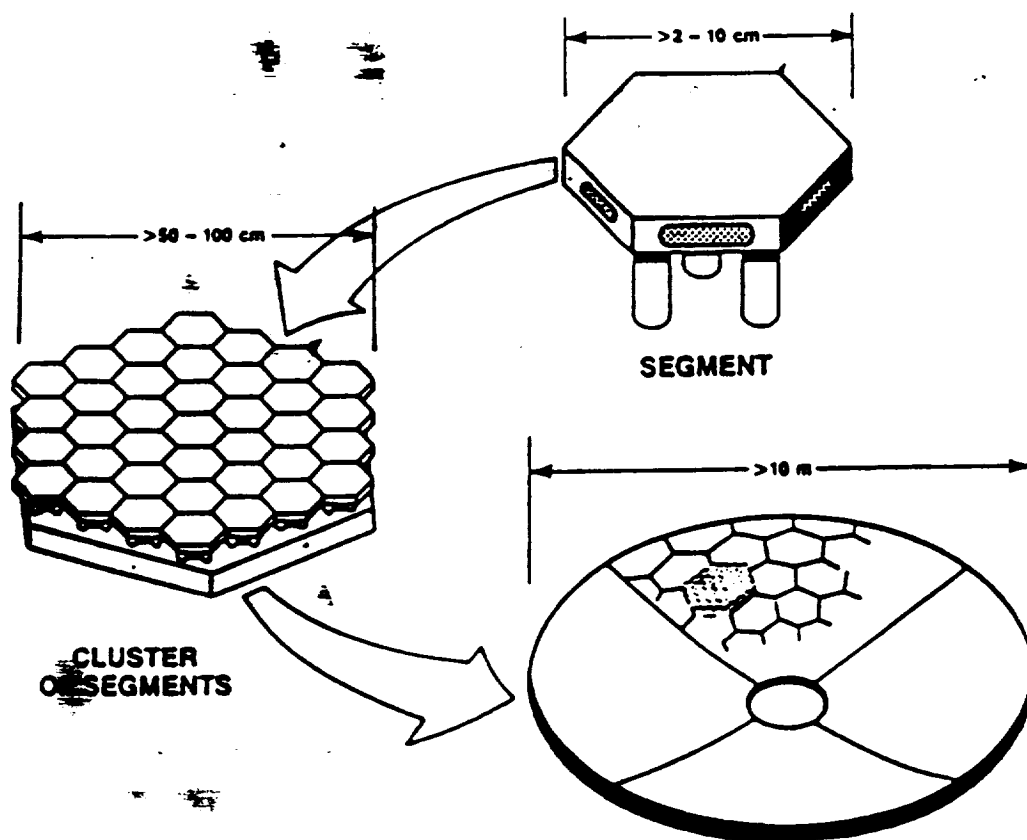
Figure 5.

Project "SELENE"

An innovative,low-cost solution to the need for large amounts
of electrical power for lunar development.

An efficient, low cost method for transportation in cis-lunar
space.

A non-nuclear method for providing high power for radar
satellites and direct broadcast satellites

by

John D. G. Rather, Ph.D.
Assistant Director for Space Technology (Program Development)
Office of Aeronautics, Exploration, and Technology
NASA Headquarters
Washington, D. C., 20546

February 5, 1991 Presentation

BOOTSTRAPPING LARGE SCALE LUNAR DEVELOPMENT

PROJECT SELENE
FEASIBILITY
DEMONSTRATION
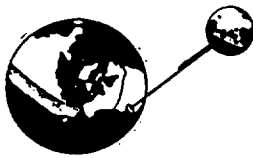
SELENE
POWER
SYSTEM

LUNAR
DEVELOPMENT
AUTHORITY

COMPLETION
EARLY 1994

COMPLETION
1998

MATURE 2008
(OPEN ENDED EXPANSION)

91-1023

PROJECT SELENE FEASIBILITY DEMONSTRATION

PURPOSE: TO SHOW ABILITY TO PROJECT NEAR-DIFFRACTION-LIMITED LASER BEAM TO THE MOON IN THE NEAR TERM.

2 Kilowatt Laser

Apollo Laser
Retro Reflectors
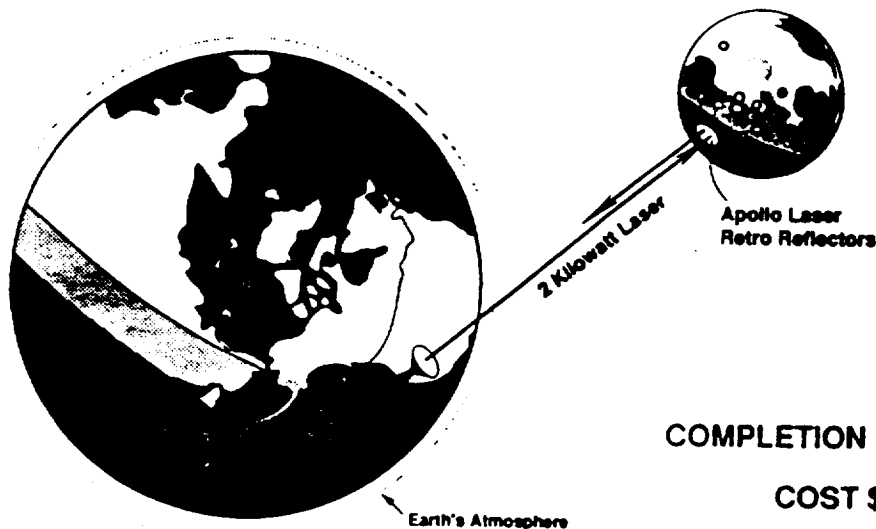
COMPLETION EARLY 1994

COST $80M

Earth's Atmosphere

91-1024

SELENE POWER SYSTEM

PURPOSE: TO PROVIDE MEGAWATTS OF ELECTRIC POWER
- ● FOR LEO TO LLO PROPULSION
- ● FOR LUNAR BASE DEVELOPMENT

Earth's Atmosphere

2 Megawatt Lasers

- ● Requires three laser sites on Earth separated by eight time zones

COMPLETION 1998

COST $2.5B

Laser Electric Propulsion

91-1027
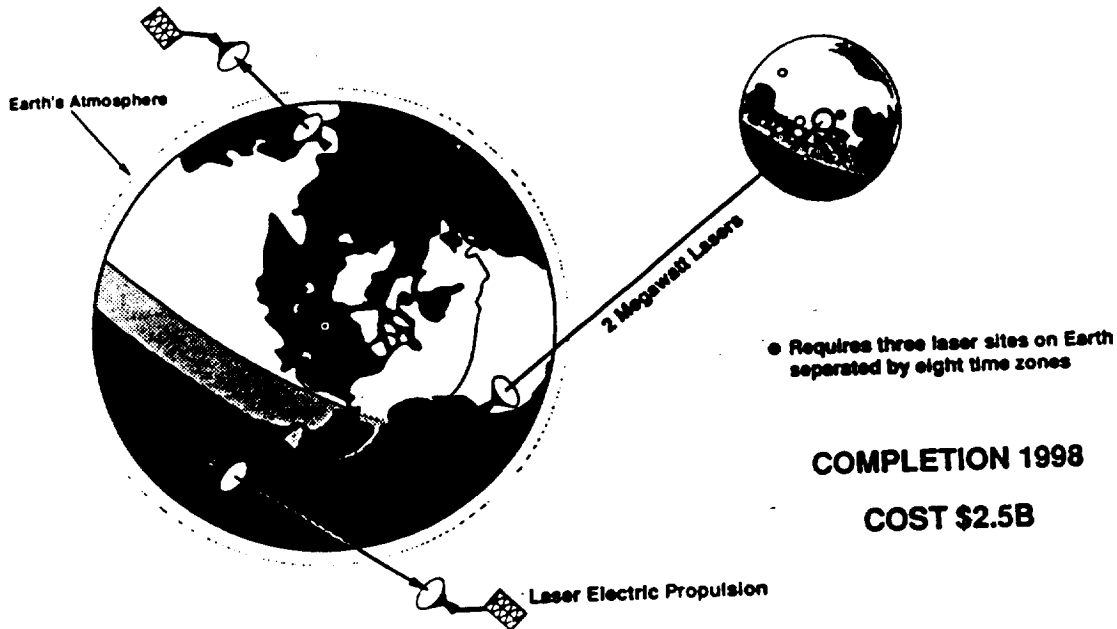
LUNAR DEVELOPMENT AUTHORITY

PURPOSE: TO DEVELOP SOLAR POWER ON THE MOON AND BEAM ENERGY TO USERS ON EARTH VIA EFFICIENT LASERS.

Electric Catapult to GEO

- ● Interconnected Solar Power Stations Surrounding Lunar Poles

- ● 200 Megawatt Laser Arrays for Power Transmission

GEO

**MATURE 2008
(OPEN ENDED EXPANSION
PAYS FOR ITSELF)
INITIAL COST $20B**

Earth's Atmosphere

Relay mirrors in high orbits

91-1028

B-4

TYPICAL ATMOSPHERIC TRANSMITTANCE TO SPACE FROM 3 KM MOUNTAIN PEAKS
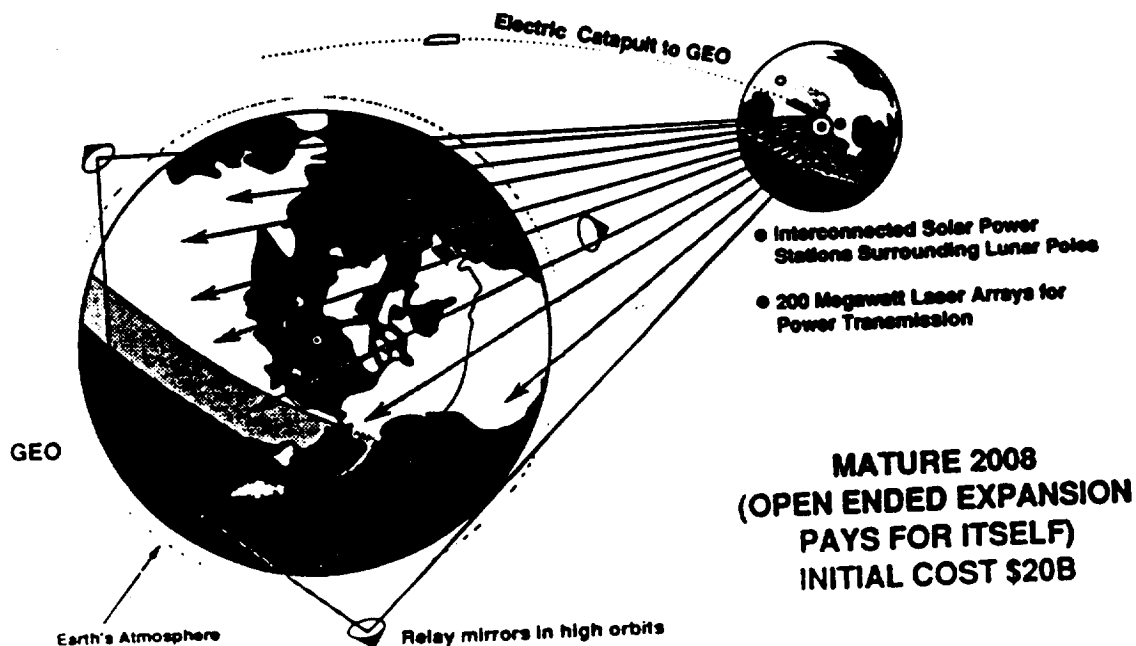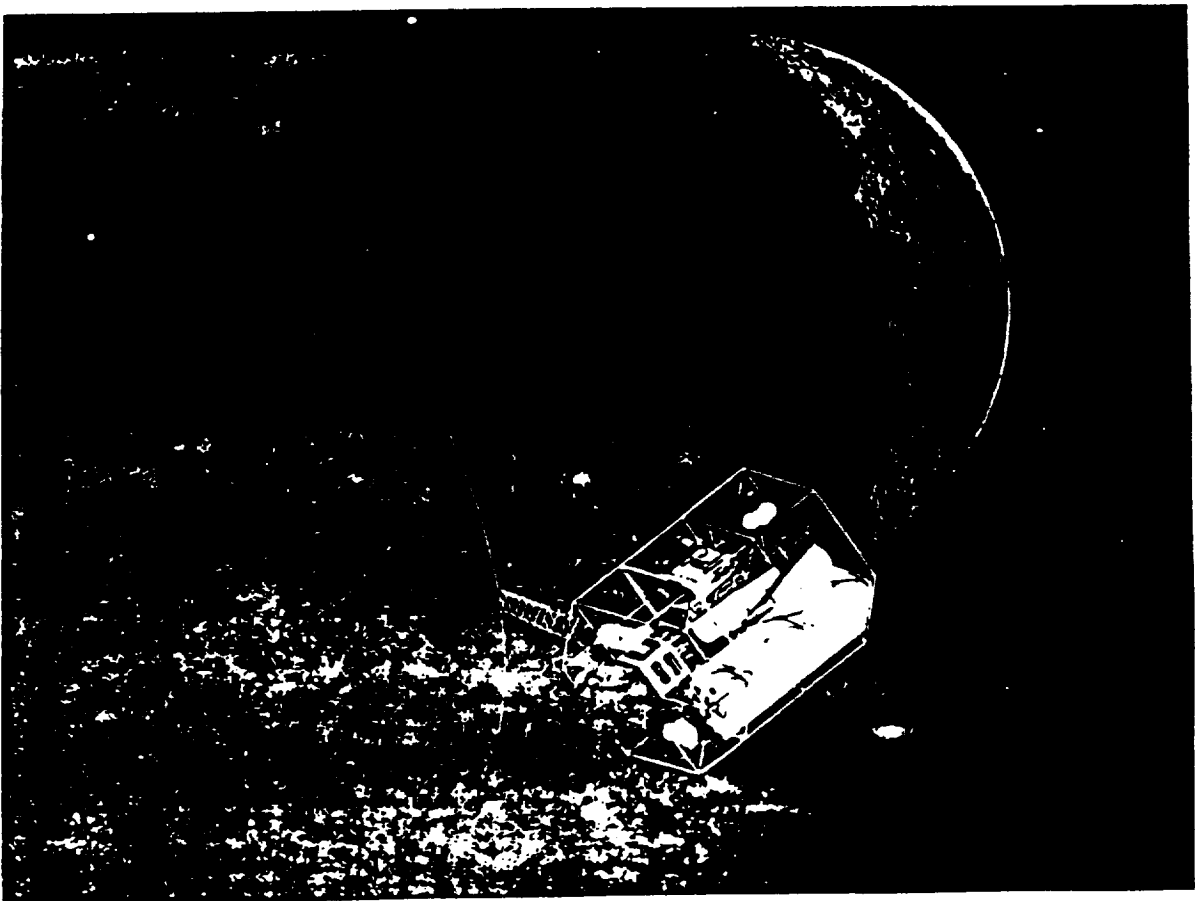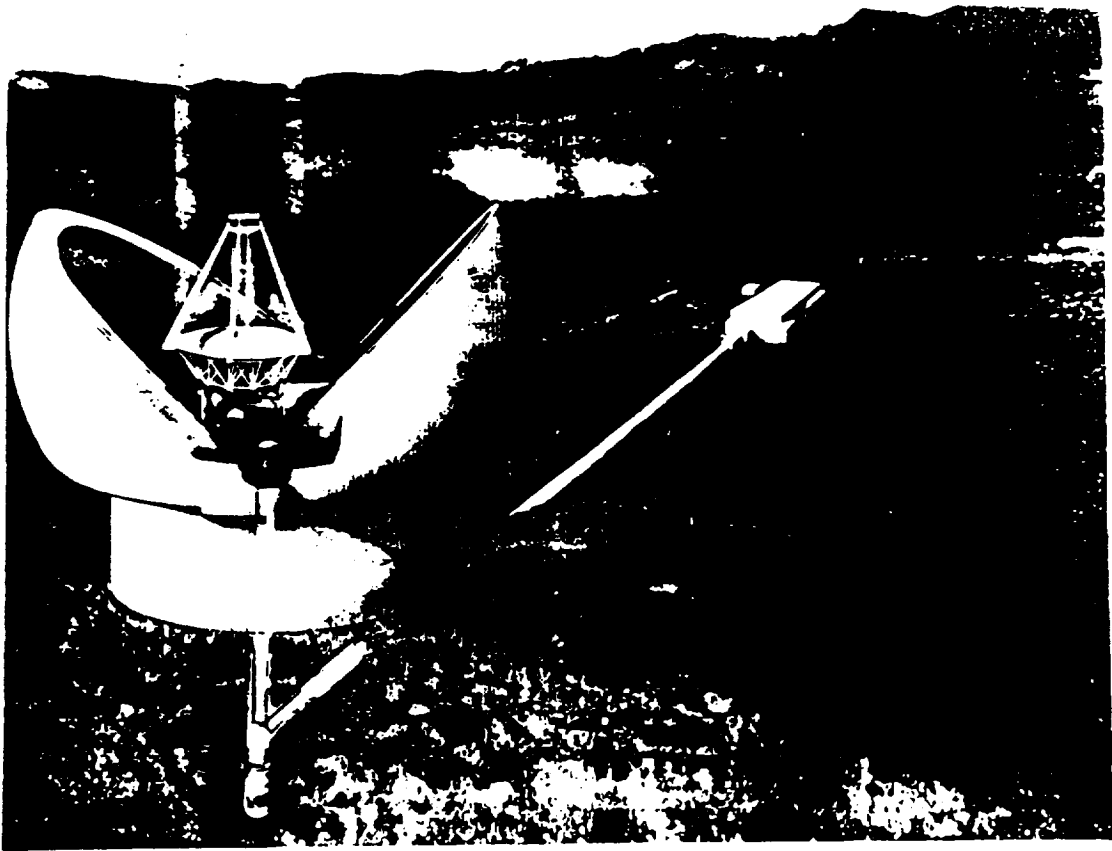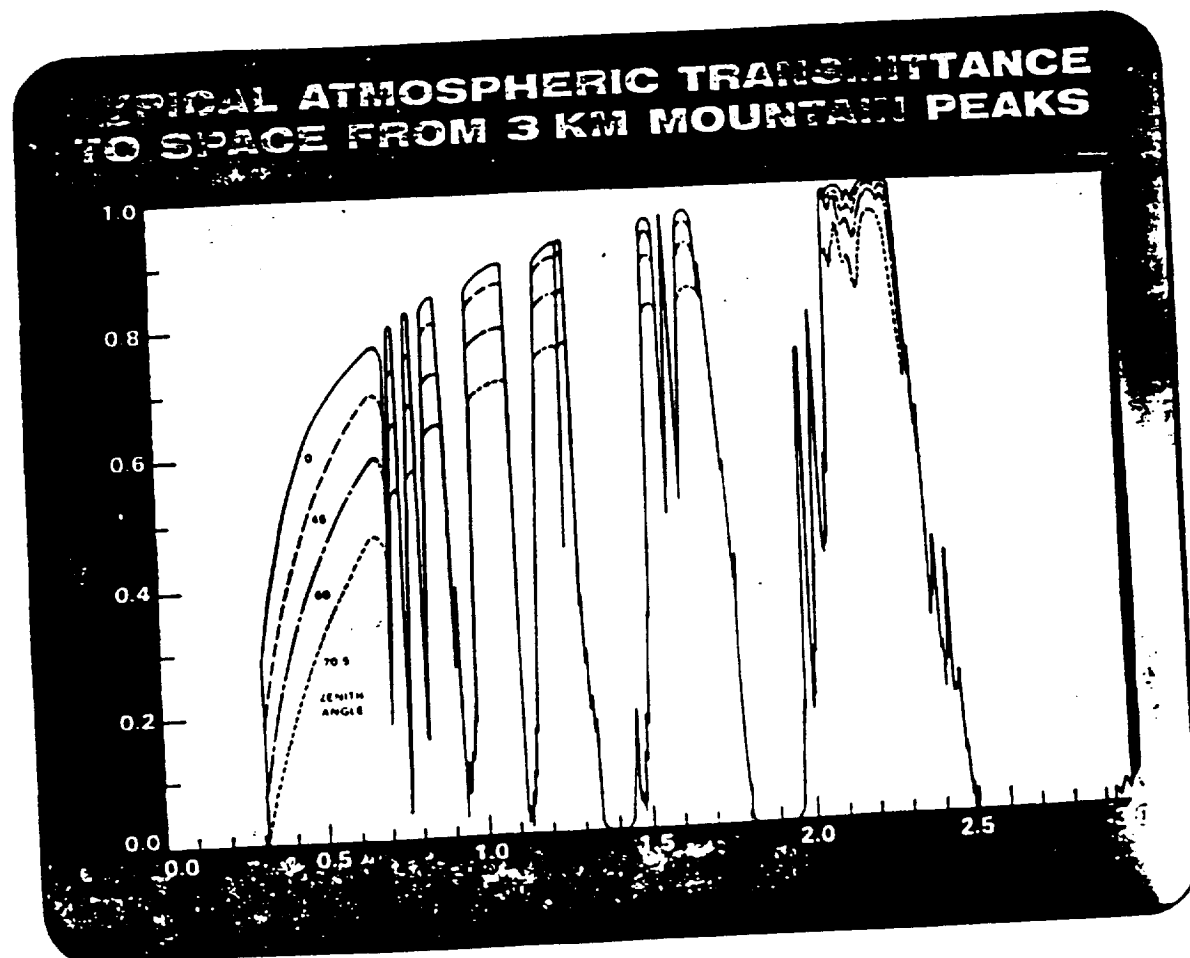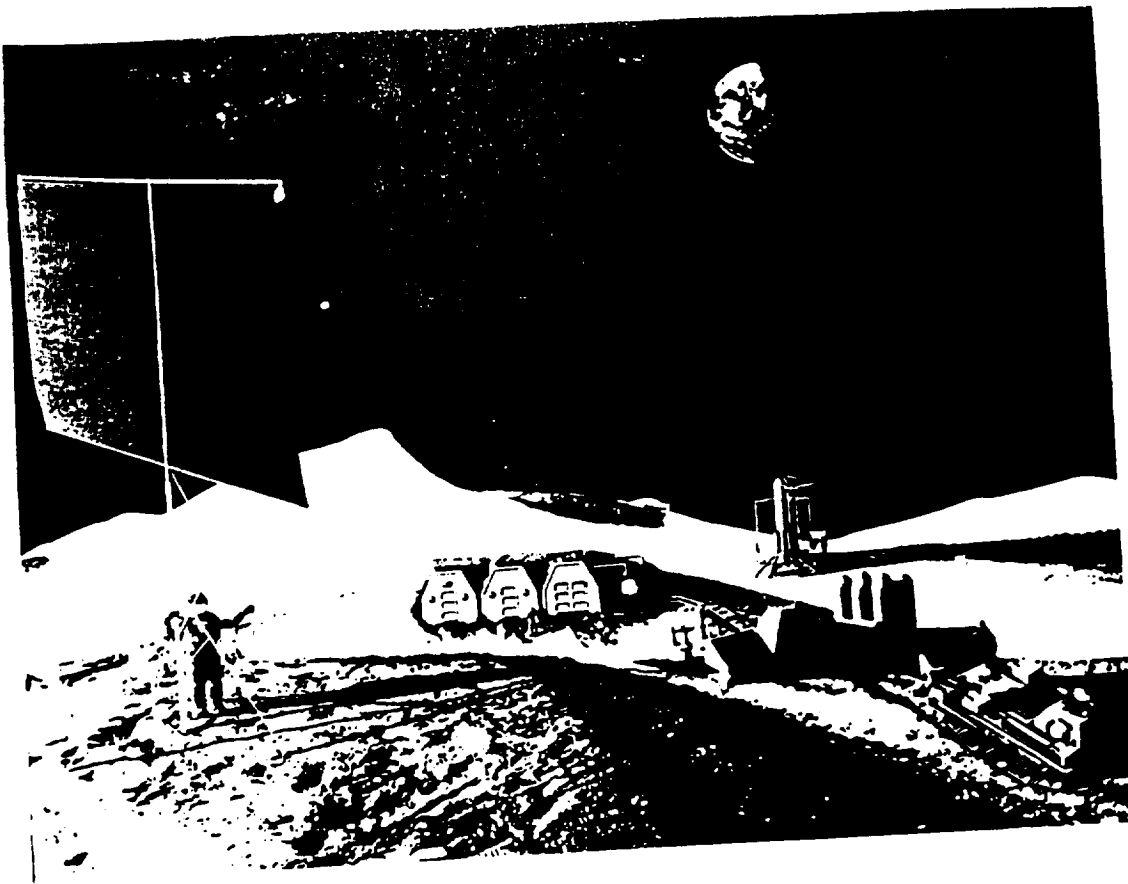
BASIC ELEMENTS OF A COMPTON-REGIME FREE ELECTRON LASER

WIGGLER MAGNET ARRAY

OUTPUT MIRROR

rf ELECTRON ACCELERATOR

TOTAL REFLECTOR

$$\lambda_s = \frac{\lambda_w}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$K = e\lambda_w B/2\pi mc^2$$
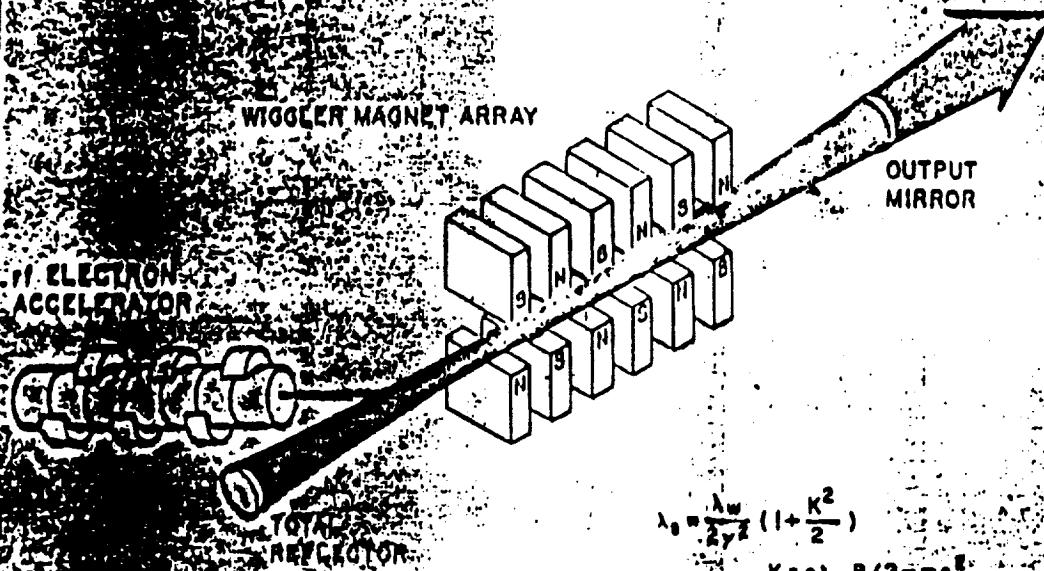
Physics and Mathematics

COMPONENT TECHNOLOGIES FOR MULTI-MEGAWATT MASTER-OSCILLATOR POWER AMPLIFIER

Electron beam source

Accelerator modules

Magnetic pulse sources

Induction Linac

High power electron beam

Optical beam expander

Wiggler

Electron beam dump

B-6
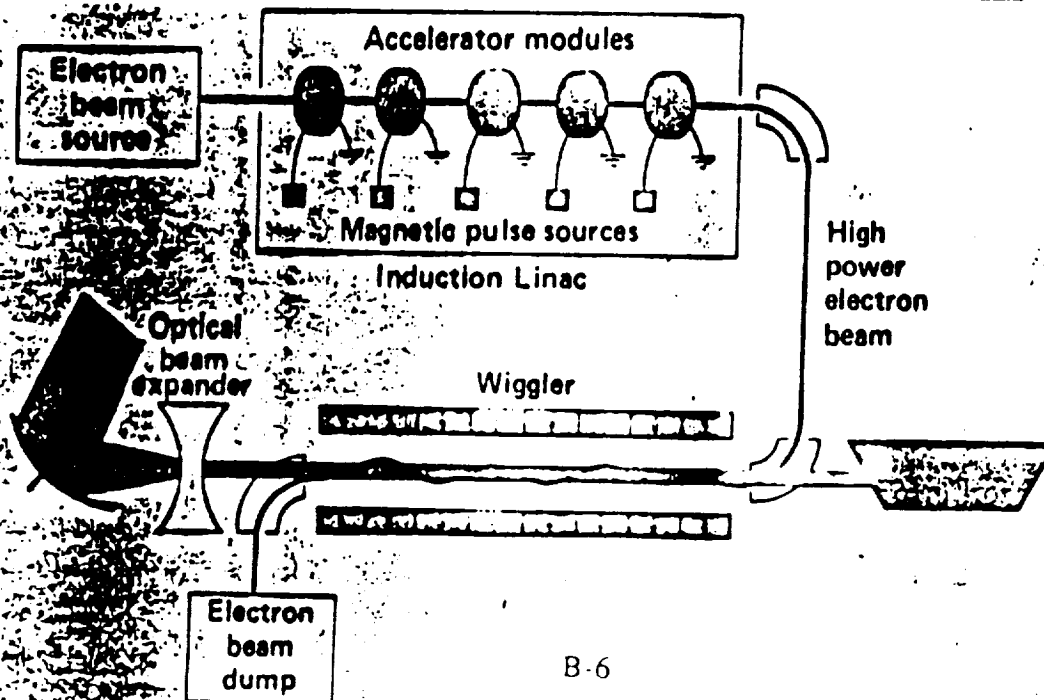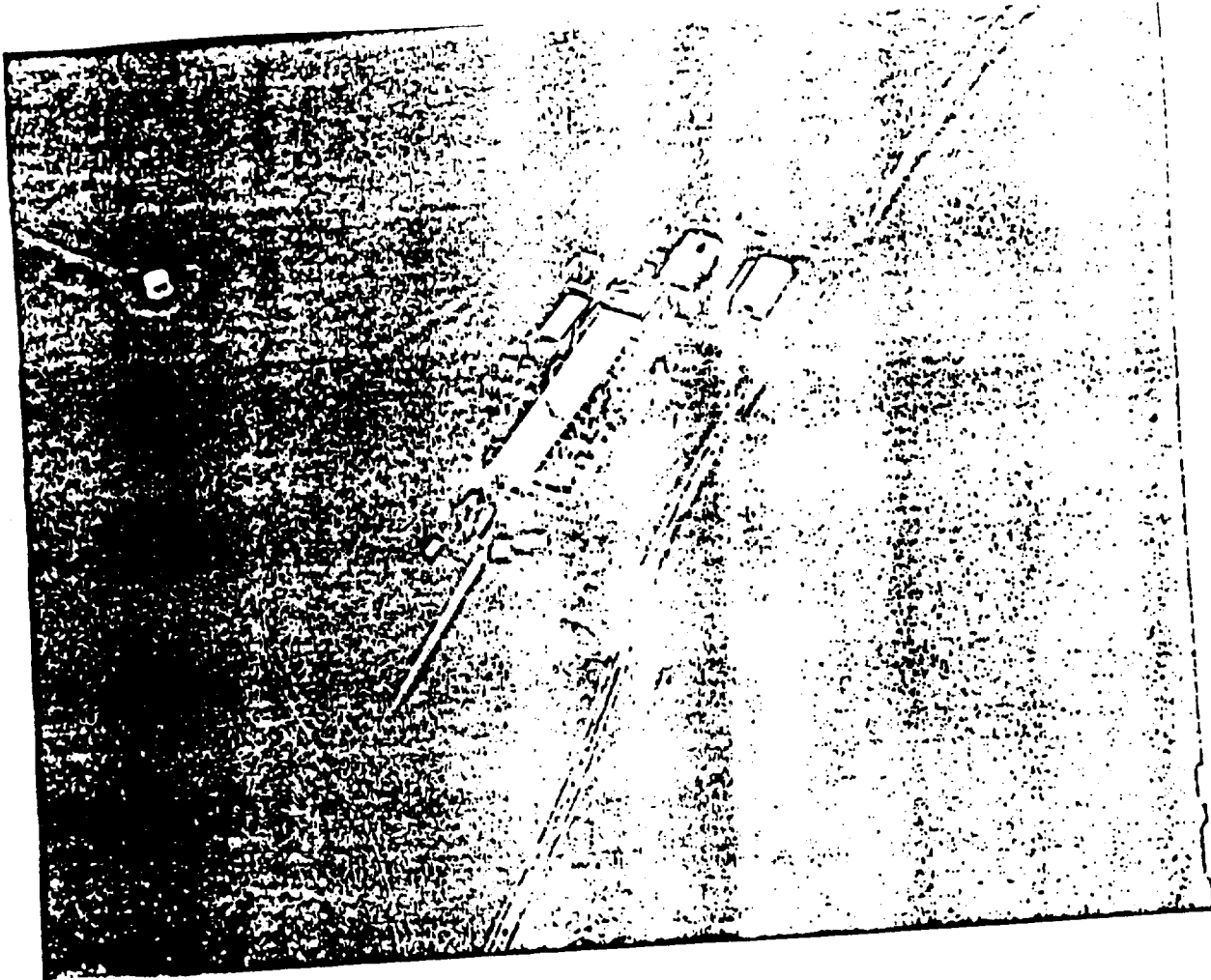
A 10-METER TELESCOPE
for
MILLIMETER AND SUB-MILLIMETER ASTRONOMY
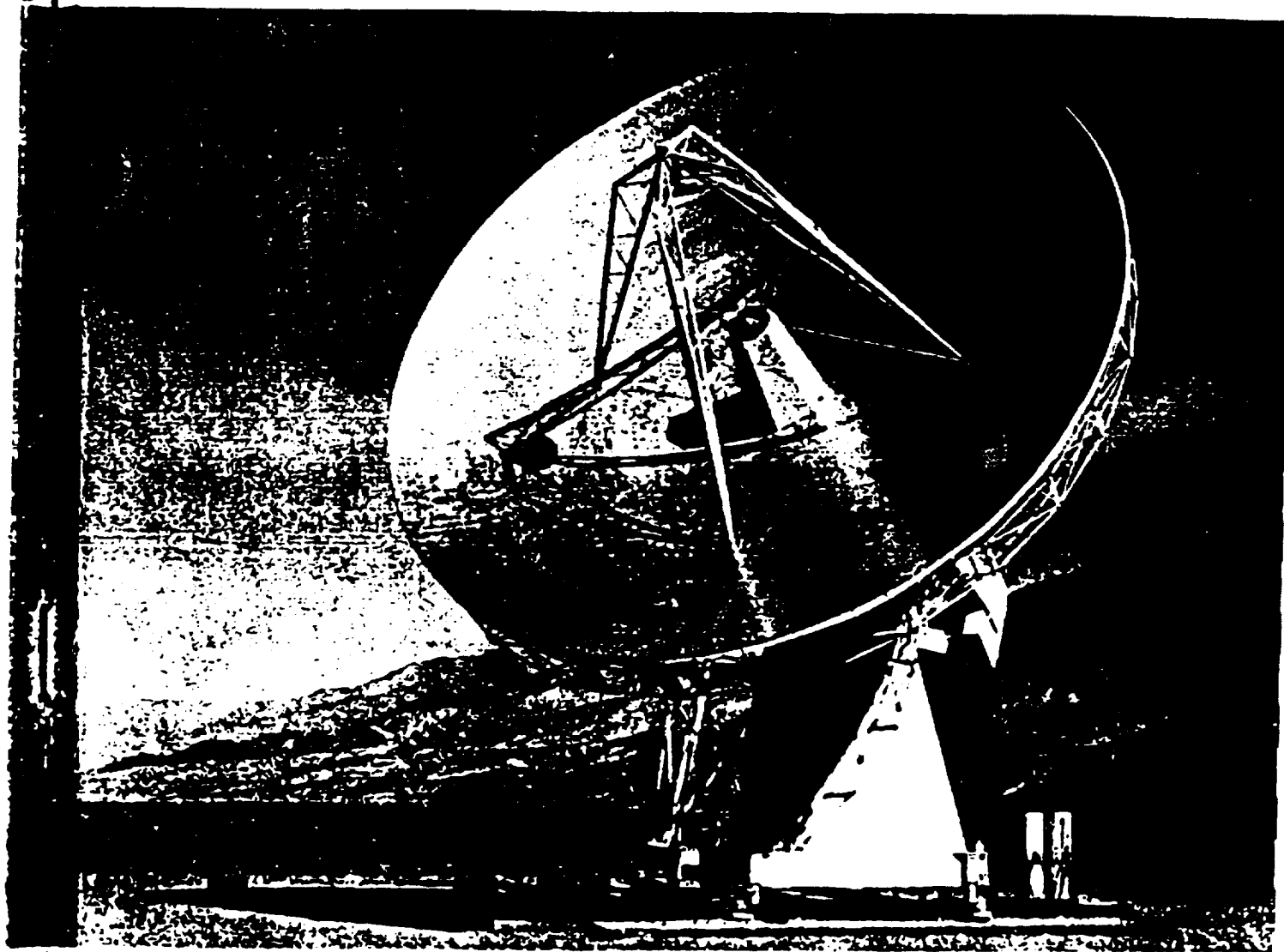
Robert B. Leighton
California Institute of Technology

May, 1978

B-8
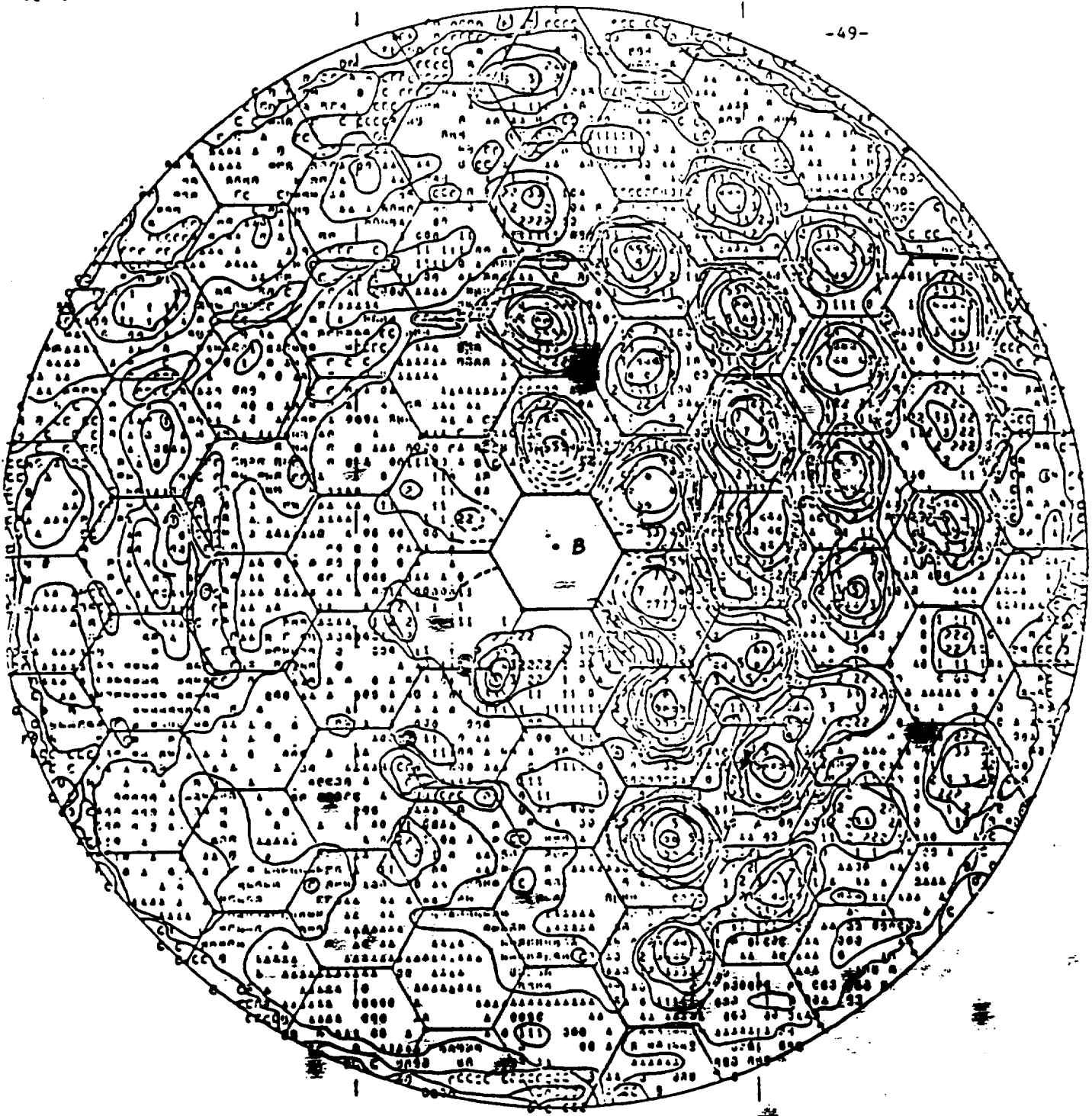
Figure 15: Computer map of prototype dish surface as measured following the initial remounting of the panels. Approximate boundaries of the panels are drawn in, and approximate, hand-drawn contours are shown. Positive heights above a best-fit paraboloid are indicated by the digits 0-9, negative heights by the letters A-I, in 25 um (0.001 inch) steps. If a given point does not fall within ± 1/4 unit of an integer value, a blank is printed. The panels to the left of the heavy jagged line had "stretchers" attached and those to the right did not (see text). Note the obvious "crowning" of the unstretched panels as compared with the stretched ones. The rms surface errors for the two areas are 30 um and 60 um respectively, and the mean value is 50 um.

Figure 14

>2 - 5 cm

Segment

>50 - 100 cm

Cluster of Segments

>10 m

Full Aperture
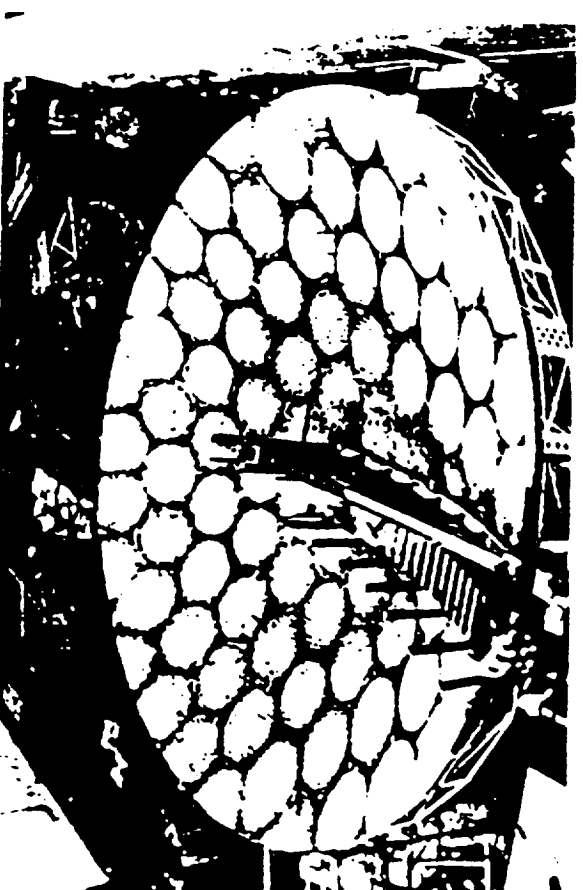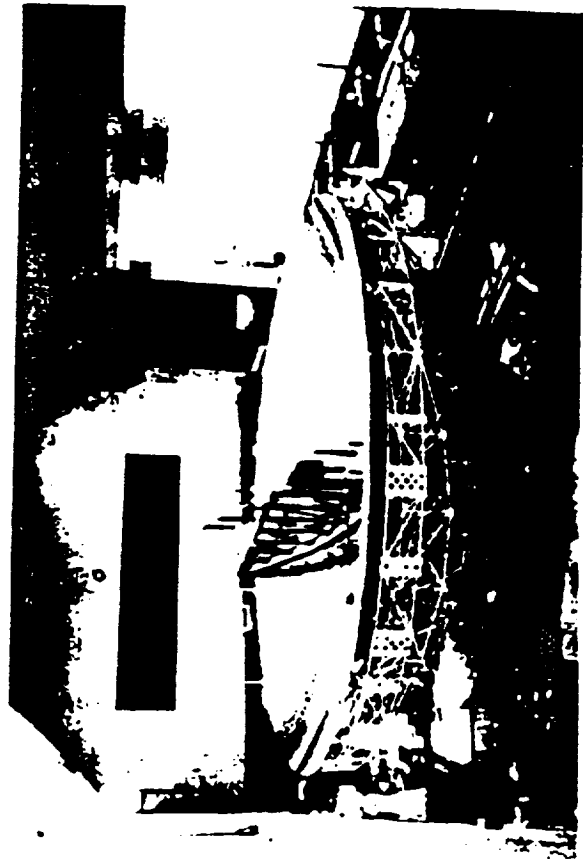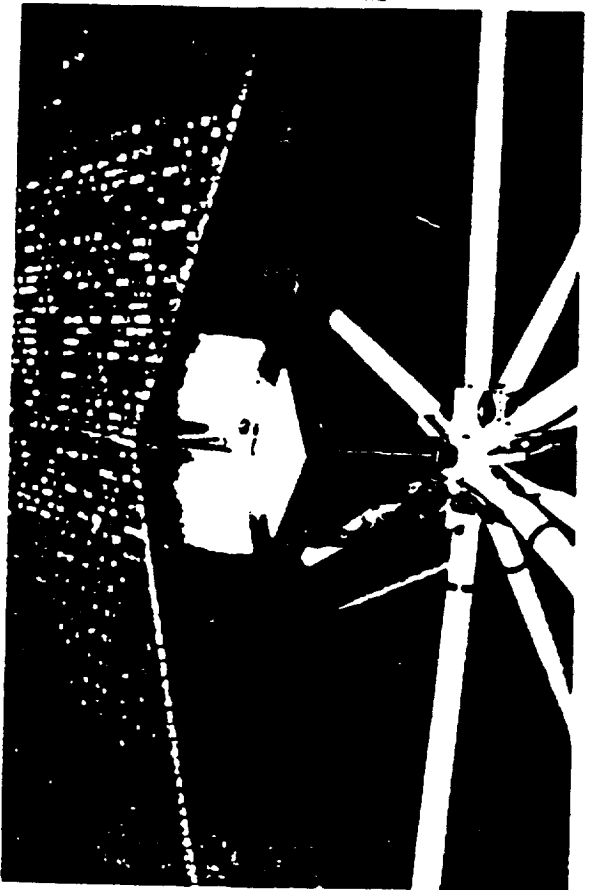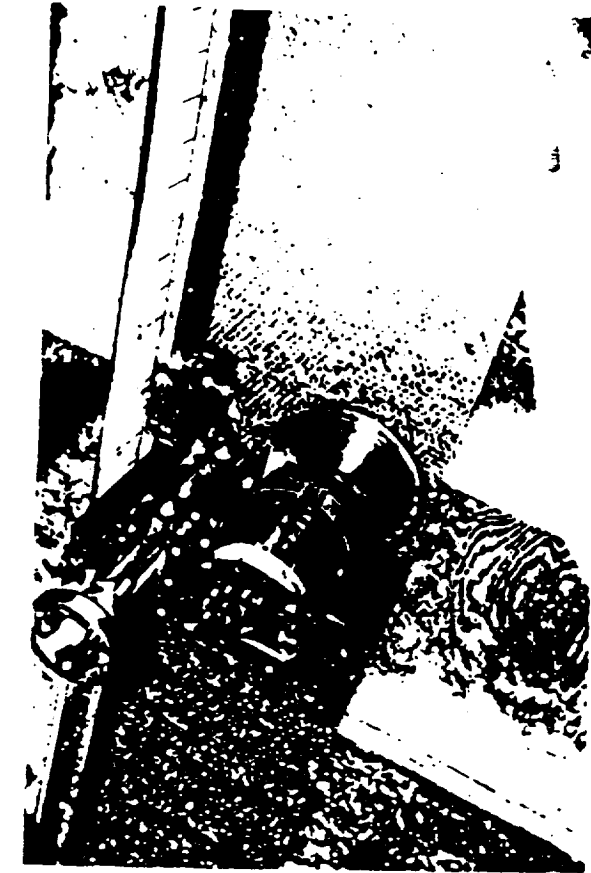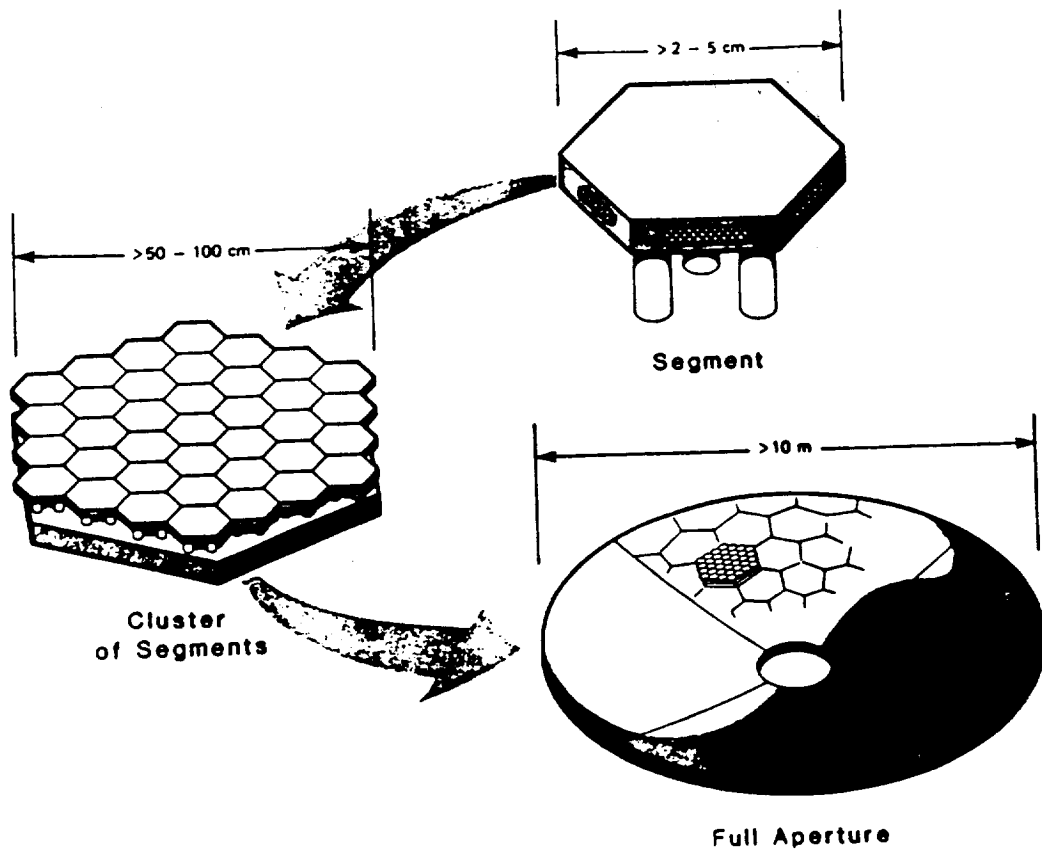
PAMELA — A LOWER COST
HIGH RESOLUTION IMAGING APPROACH

CONVENTIONAL ADAPTIVE OPTICS CONCEPT

WAVEFRONT MIRROR

WAVEFRONT RECONSTRUCTOR

GRADED GLASS

CONTROL SIGNALS

BEAM SPLITTER

COMPENSATION SYSTEM

FOCAL PLANE

MONOLITHIC MIRROR

SUPPORT STRUCTURE

PAMELA

CONTROL SIGNALS TO PRIMARY COMPENSATION SEGMENTS

WAVEFRONT SENSOR

FOCAL PLANE

BEAM SPLITTER

SEGMENTED MIRROR
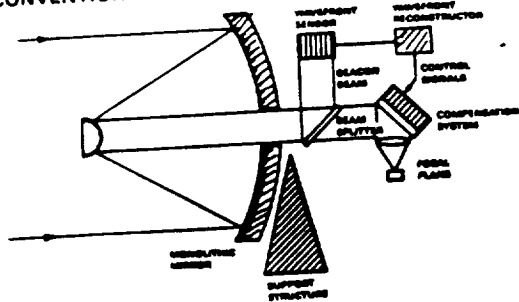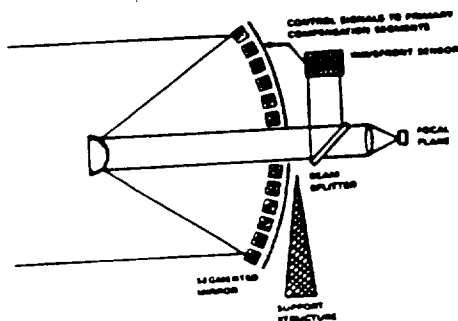
SUPPORT STRUCTURE

	CONVENTIONAL ADAPTIVE OPTICS	PAMELA
PRIMARY	MONOLITHIC OR LARGE SEGMENTS	MASS PRODUCED SEGMENTS
SECONDARY		
SUPPORT STRUCTURE		
WAVEFRONT SENSOR		
WAVEFRONT RECONSTRUCTOR		NOT REQUIRED
CONTROL PROCESSOR	MULTI CHANNEL	ON BOARD 1 PER SEGMENT
COMPENSATION MIRROR	HIGH DENSITY MEMBRANE OR SEGMENTS	ACTUATORS ONLY

○ MOST EXPENSIVE

● LEAST EXPENSIVE

B-11

TTPM FUNCTIONAL BLOCK DIAGRAM

BEAM INCIDENT
ON ONE ELEMENT

ONE OPTICAL MEASUREMENT
PER SEGMENT

TILT SENSING
WAVEFRONT
MONITOR
(SINGLE CHANNEL)

EDGE SENSOR SIGNALS
CONTROL AVERAGE PHASE

$\Delta\Phi$ $\Delta\Theta_1$ $\Delta\Theta_2$

SEGMENT
ACTUATOR
ELECTRONICS

ΔP_1

ΔP_2

ΔP_3

SIGNAL
CONDITIONING
ELECTRONICS

SUBSYSTEM CONTAINED ON EACH SEGMENT
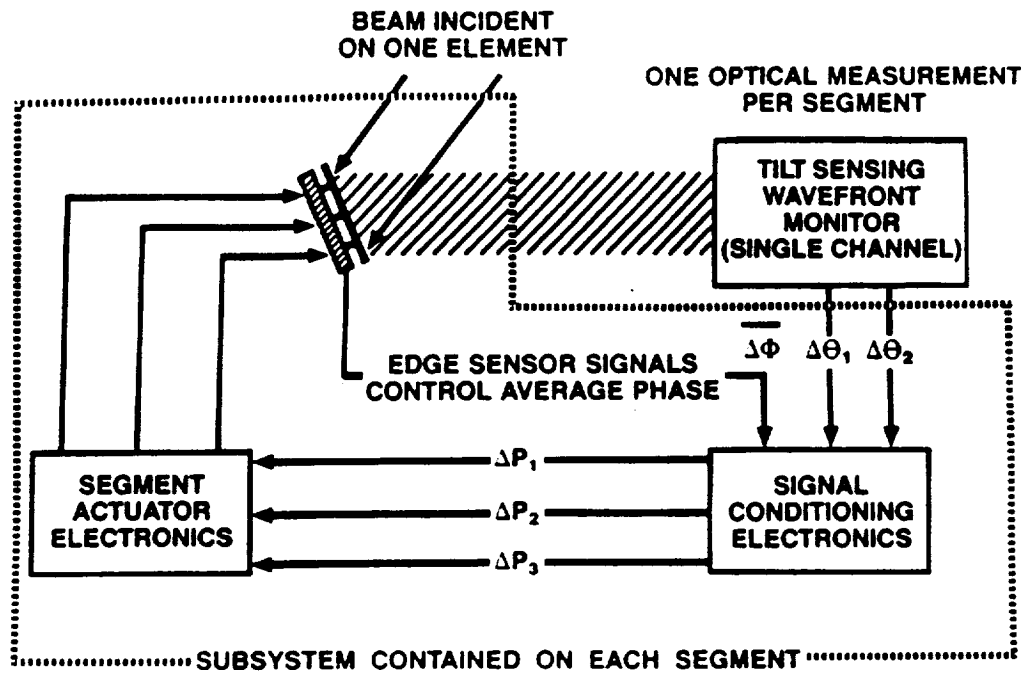
ARRANGEMENT OF SENSING COILS
ON SEGMENT EDGE
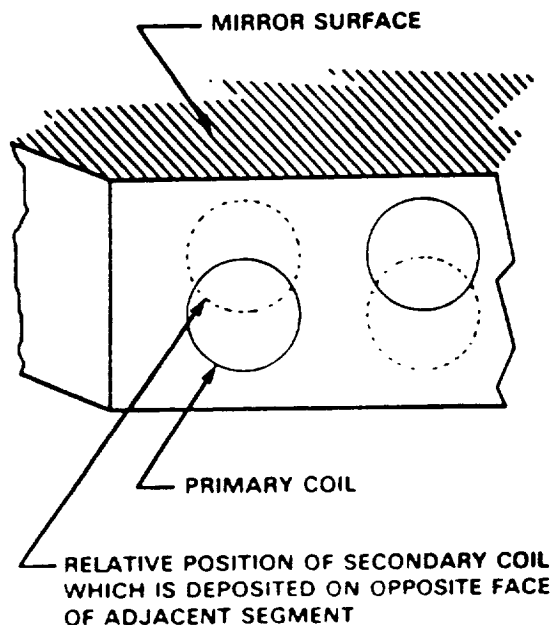
MIRROR SURFACE

PRIMARY COIL

RELATIVE POSITION OF SECONDARY COIL
WHICH IS DEPOSITED ON OPPOSITE FACE
OF ADJACENT SEGMENT

B-12

MIRROR AREAL MASS DENSITIES AS A FUNCTION OF SEGMENT SIZE

KG/M²

HUBBLE

CURRENT TECHNOLOGIES

PAMELA

SEGMENT SIZE (CM)

ACTUATOR DETAIL

REAR SURFACE OF SEGMENT

FLEXURE

CENTRAL POLE PIECE

BUSHING

COIL WINDING

BACK-UP STRUCTURE

LEGEND

MAGNET	
VANADIUM	
ALUMINUM	
COMPOSITE	
Be Cu	

SCALE

10mm
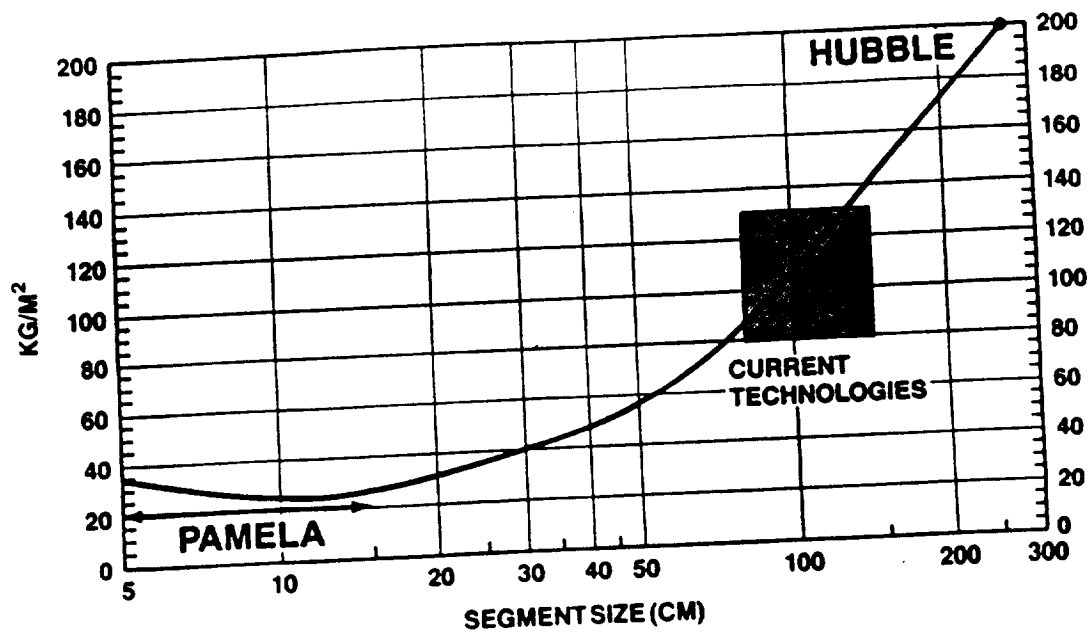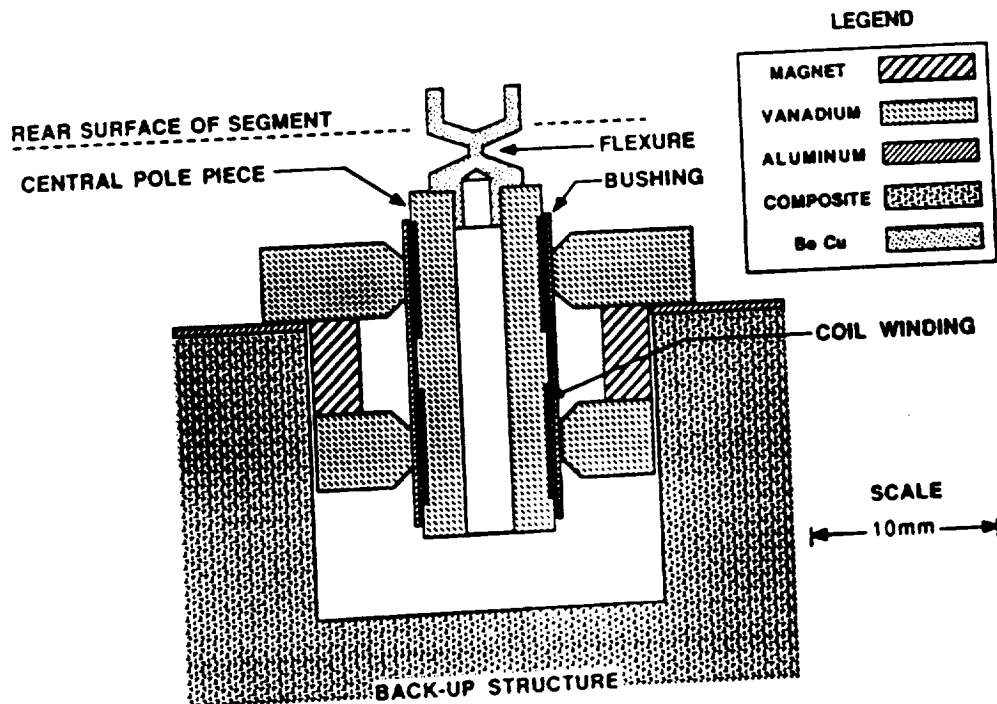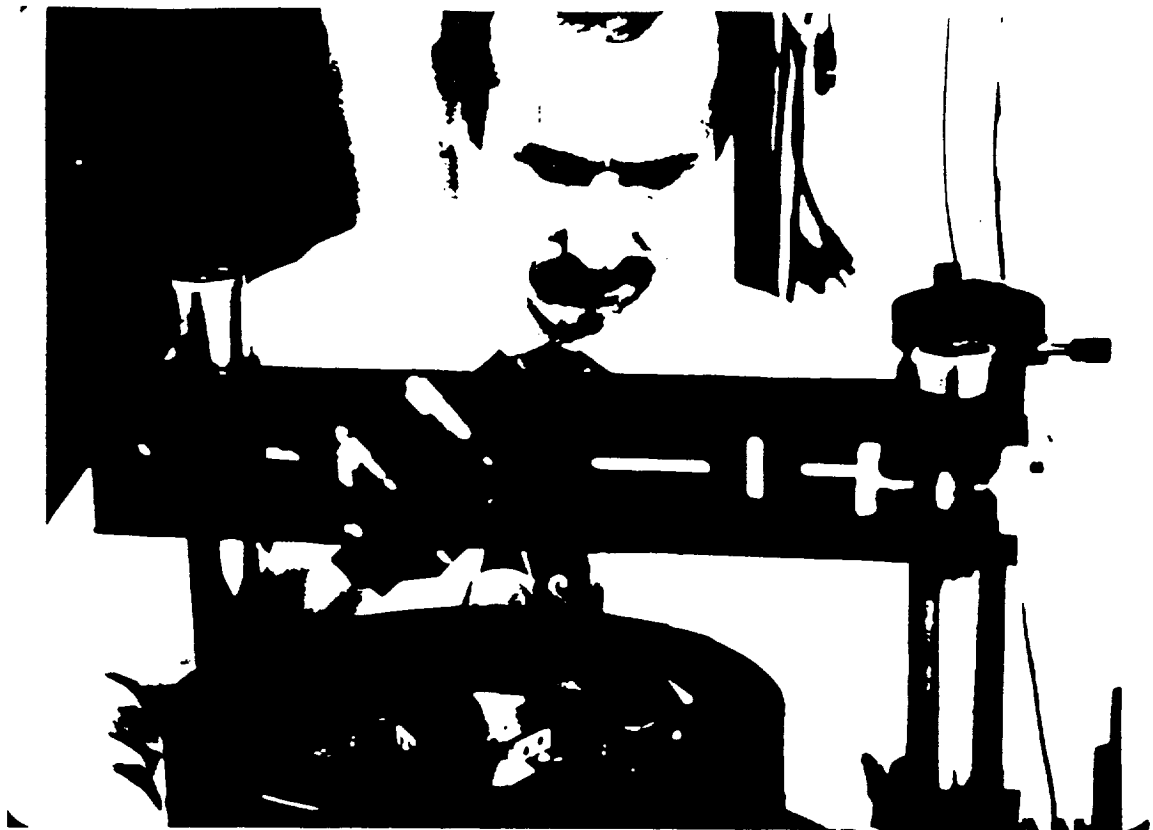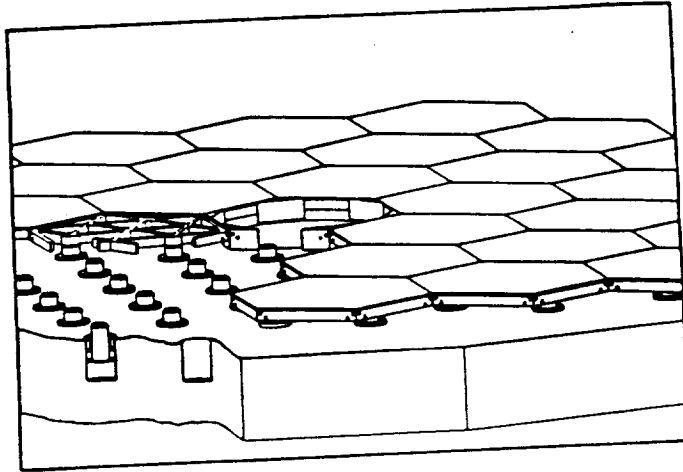
SUCCESSIVE OVER-RELAXATION—
SIX SENSOR EDGES

$$\omega = \frac{2}{1 + \sin\,[\pi/(N+1)]}$$
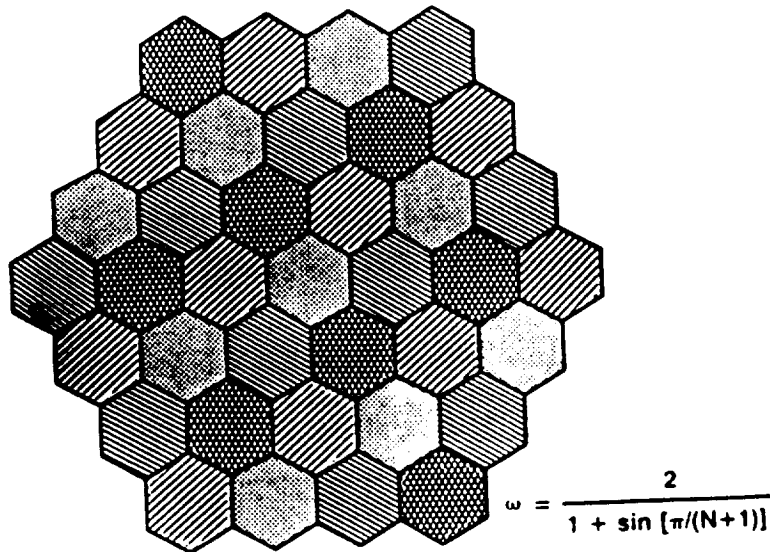
WHERE N IS THE NUMBER OF ELEMENTS ON A SIDE
(N² TOTAL ELEMENTS).

ALGORITHM TRANSIENT RESPONSE
(SEVEN RINGS OF HEXAGONS)

LEAST SQUARES ALGORITHM

INNER ALGORITHM

RELATIVE BANDWIDTH = 6,400

RELATIVE BANDWIDTH = 15,000

STREHL
RATIO (%)

0.06λ
(THEORETICAL
VALUE)

WAVEFRONT ERROR

OCCURENCES
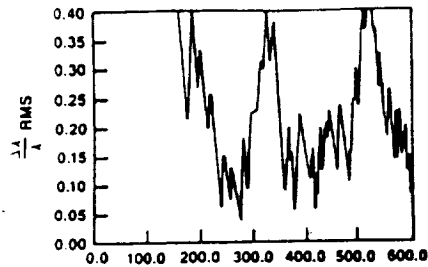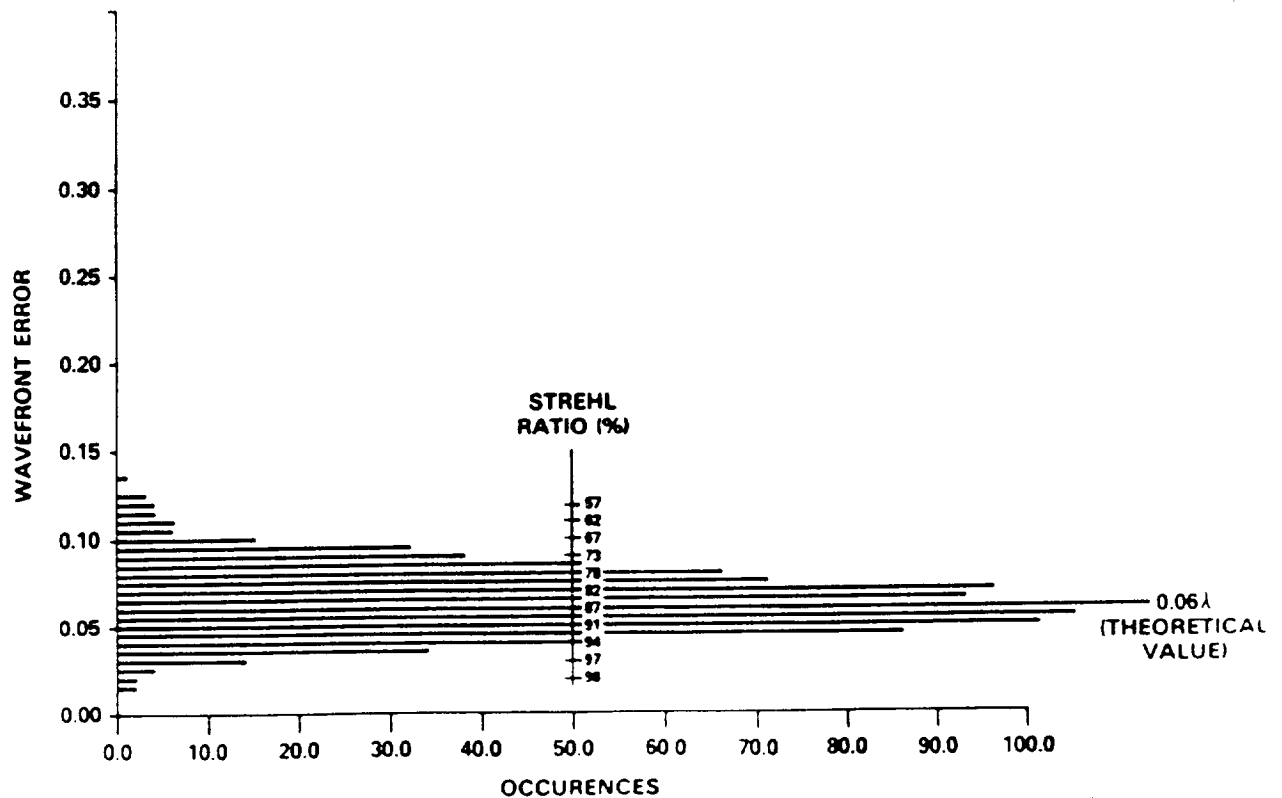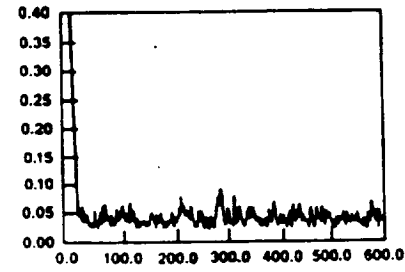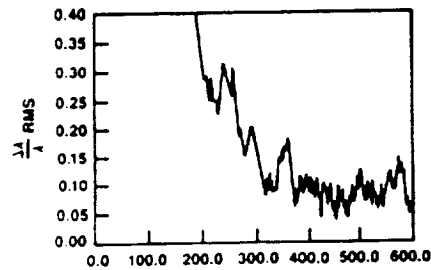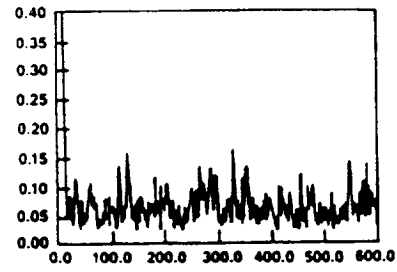
SURFACE SETTING ALGORITHMS
STEP FUNCTION RESPONSE (CONVERGENCE TIME)
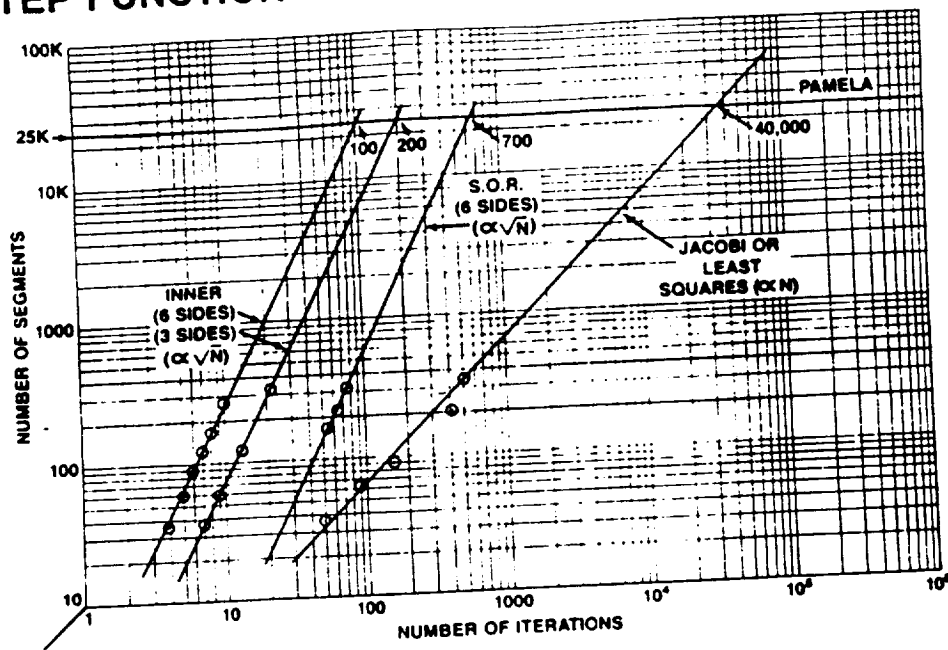
STEPS IN RAPID CONVERGENCE ALGORITHM

- EDGE MATCH ALL SEGMENTS

- MEASURE TILTS OF ALL SEGMENTS

- APPLY AND FIX SEGMENT TILTS WHILE EDGE MATCHING

- COMPUTE PISTONS OF ALL REFERENCE SEGMENTS AT CENTER OF EACH CLUSTER BY INTEGRATING TILTS ALONG SPECIFIED PATHWAYS (RELATIVE TO MASTER SEGMENT)

- ADJUST AND FIX PISTONS OF REFERENCE SEGMENTS AT CENTER OF EACH CLUSTER

- PISTONS OF REMAINING SEGMENTS WITHIN EACH CLUSTER ARE ADJUSTED BY EDGE MATCHING TO REFERENCE SEGMENT

⬡ REFERENCE SEGMENTS

⬡ DEFINES CLUSTERS

➡ POSSIBLE PATHWAYS OF PISTON COMPUTATION

B-17
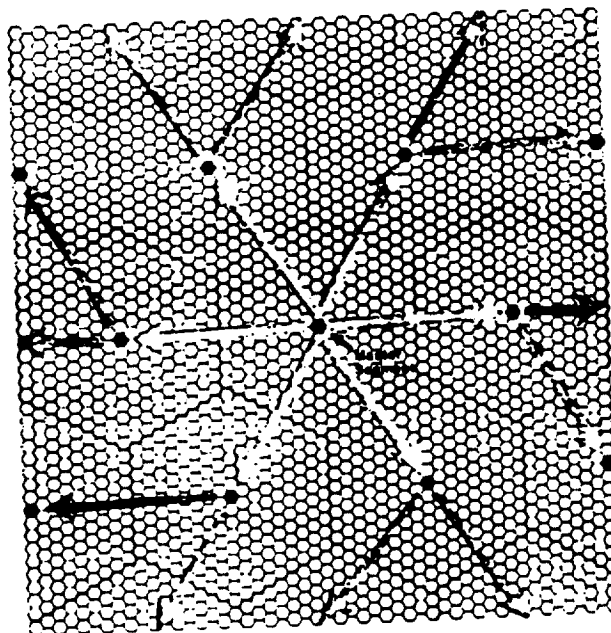
Lunar Retro-returns for adaptive correction

- Number of photocounts per sub-aperture per frame

$$N_{sa} = \left(\frac{J_0 \sigma_{cc}}{(1.2 \, \lambda R/D)^2}\right) \left(\frac{T^2 E^2 \eta}{h\nu}\right) \left(\frac{r_0}{R}\right)^2$$

- Parameters used for calculations:

| Symbol	Definition	Value
N_{sa}	Photocount per sub-aperture per frame	10^3
J_0	Joules per pulse	
η	quantum efficiency	0.8
D	transmitter aperture diameter	
T	transmittance of atmosphere	0.8
$h\nu$	photon energy	2.5×10^{-19} J
E	transmittance of optics	0.8
R	range to moon	4×10^8 m
r_0	atmospheric coherence length at 0.8 μm	0.1m
PRF	pulse repetition frequency	10^3/sec
λ	wavelength	0.8 μm
σ_{cc}	corner cube cross section	$1.7 \times 10^8 \frac{m^2}{SR}$
PAV	$(J_0)(PRF)$	

- Average power required for various aperture diameters

D	$\left(\frac{D}{r_0}\right)^2$	P_{av}
2m	400	2.7Kw
3m	900	1.2Kw
4m	1,600	680w

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Figure 4.

12 Meter Laser Beam Expander
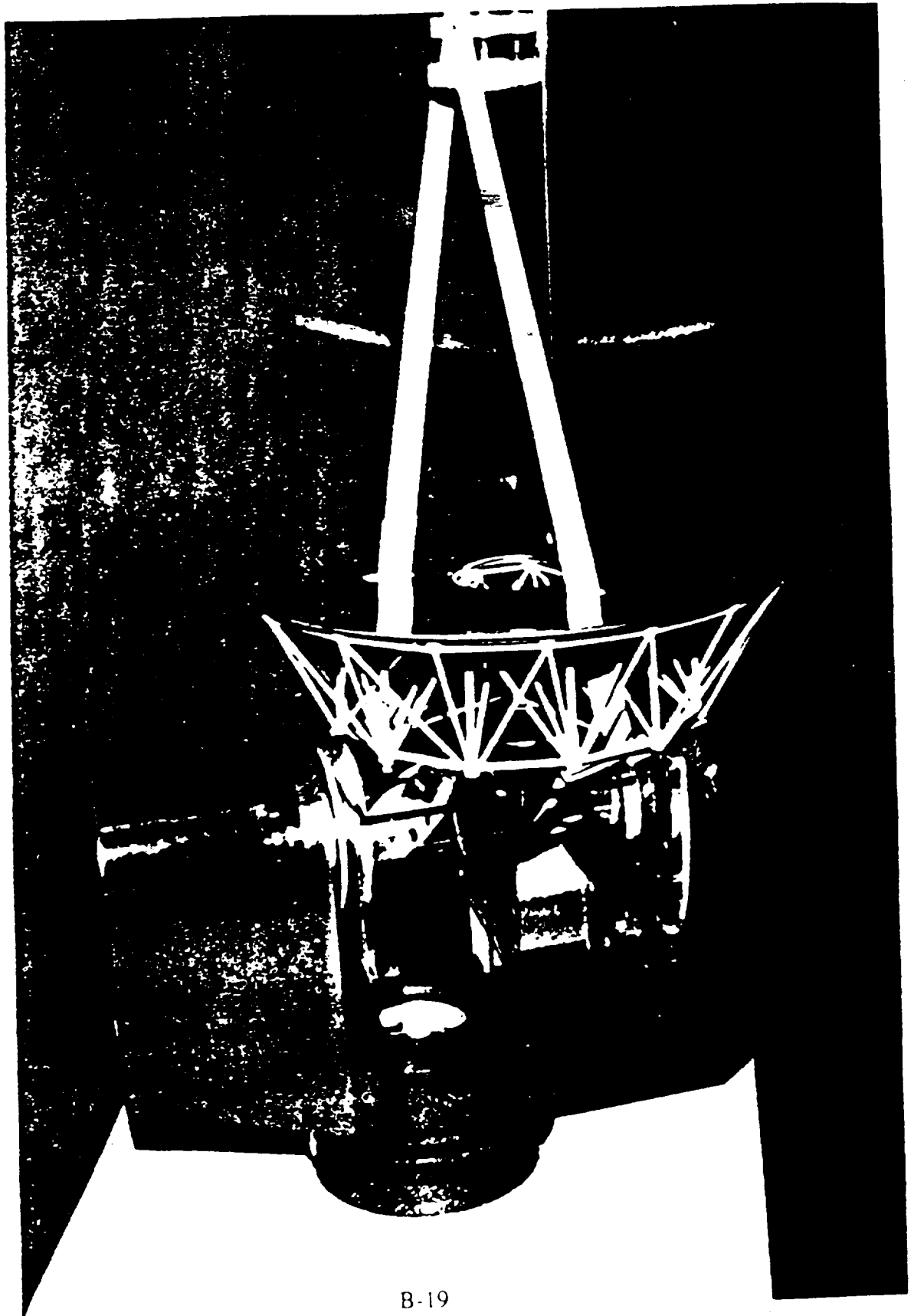
12 Meter Laser Beam Expander
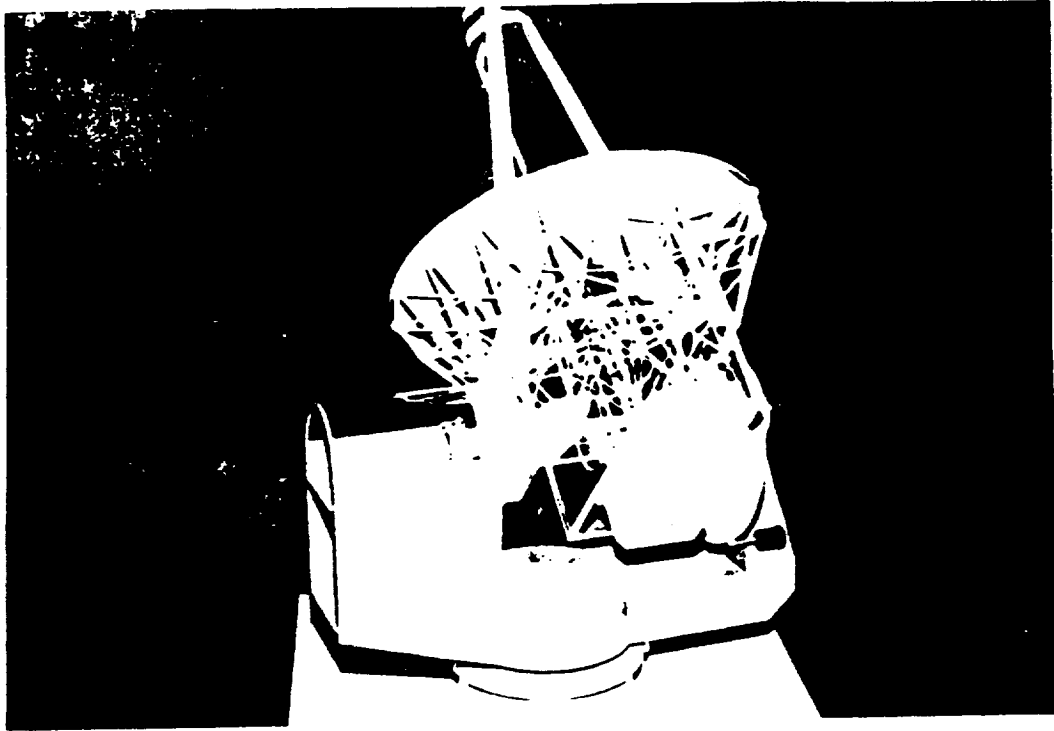
PRIORITY TASKS

- INDUSTRIALIZATION OF OPTICAL SEGMENT PRODUCTION

- CONTROL ALGORITHMS RESEARCH

- WAVEFRONT SENSOR RESEARCH

- GUIDESTAR METHOD RESEARCH

91-3005

B-20

INDUCTION LINAC DRIVEN FREE ELECTRON LASERS FOR BEAMED POWER APPLICATIONS

Presented by

Daniel Goodman

Presentation to Technology
Workshop on Laser Beamed Power

NASA Lewis Research Center
Cleveland, OH

February 5, 1991

SCIENCE RESEARCH LABORATORY

INDUCTION LINAC DRIVEN FEL
FOR BEAMED POWER APPLICATIONS

1. Introduction
   - Parameters and applications
   - FEL radiation mechanism

2. Induction Linac Driven FEL
   - FEL design
   - Accelerator design
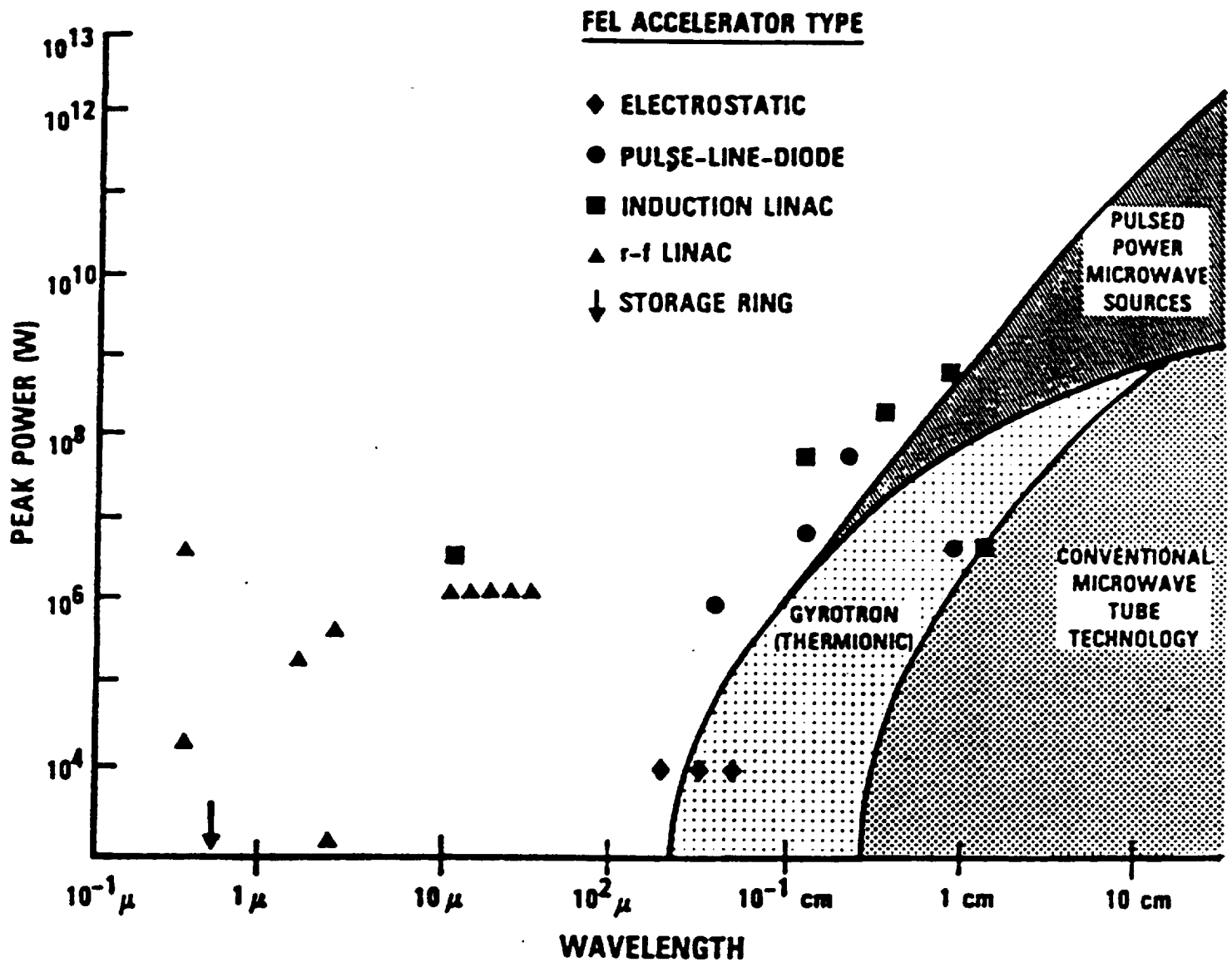   - Parameters achieved and design issues

3. Conclusions
   - Program Plan

Free Electron Lasers

- High Peak Power Achieved   (P > 10 GW)

- High Average Power Possible ($\overline{P}$ > 10 MW)

- High Efficiency ($\eta \leq 50\%$)

- Tunable over entire spectrum : visible - microwave

- Applications include :

  - Advanced accelerators
  - Advanced radars
  - Heating of fusion plasmas
  - Medical and materials research
  - Directed energy applications

FEL POWER LEVEL ACHIEVED

FEL ACCELERATOR TYPE

◆ ELECTROSTATIC

● PULSE-LINE-DIODE

■ INDUCTION LINAC

▲ r-f LINAC

↓ STORAGE RING

PEAK POWER (W)

10^{13}

10^{12}

10^{10}

10^8

10^6

10^4

PULSED POWER MICROWAVE SOURCES

CONVENTIONAL MICROWAVE TUBE TECHNOLOGY

GYROTRON (THERMIONIC)

$10^{-1}\mu$ 1μ 10μ $10^2\mu$ 10^{-1} cm 1 cm 10 cm

WAVELENGTH

SCIENCE RESEARCH LABORATORY

C-4

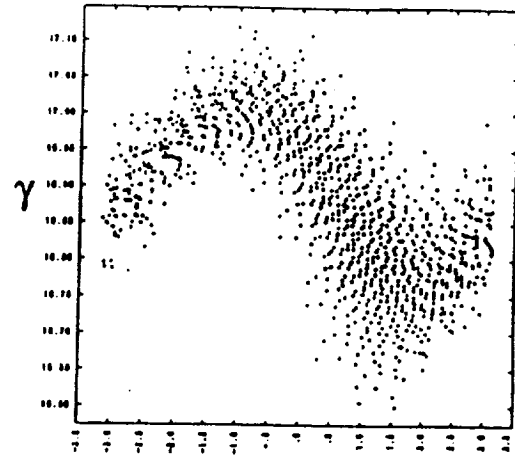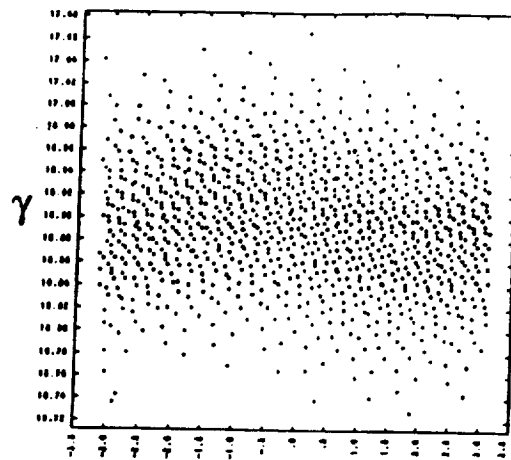# FEL RADIATION MECHANISM

- Axial bunching
  - combined wiggler and radiation fields
  - coherent radiation generation
  - trapping by ponderomotive force in "buckets"

- Tunable by varying beam voltage

$$\lambda = \lambda_w \, (1 + a_w^2 / 2) / 2\gamma_o^2$$
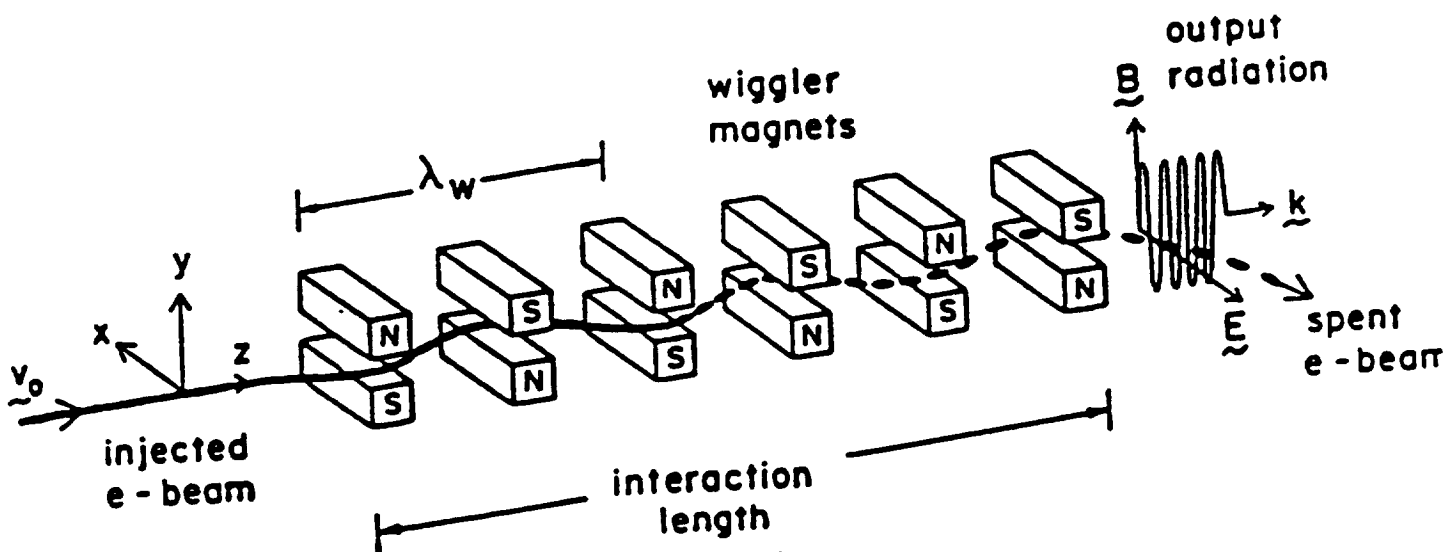
FEL RESONANT GAIN MECHANISM

- Initially Random Phase
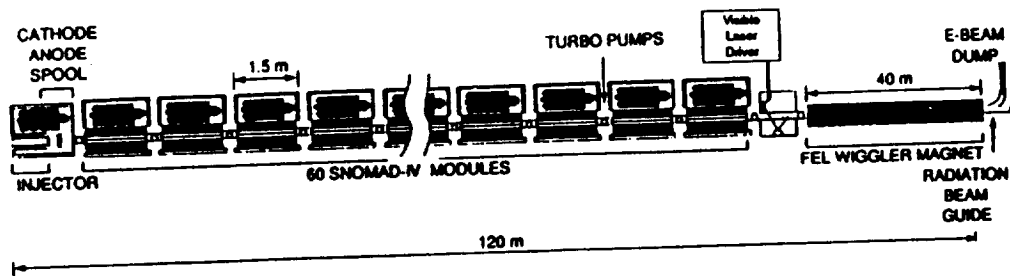- Trapping in ponderomotive potential

FEL RESONANT GAIN MECHANISM
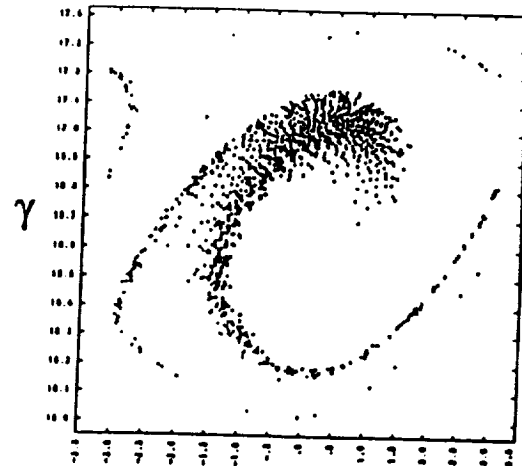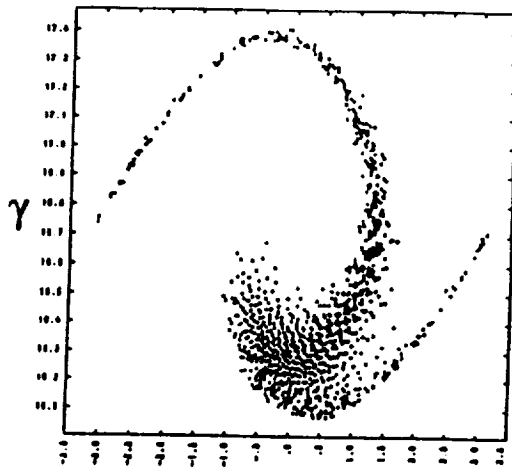
- Resonant energy transfer : particle to wave
- Saturation can be delayed by tapering
- High efficiency possible ($\eta \sim 50\%$)

CATHODE
ANODE
SPOOL

TURBO PUMPS

Visible
Laser
Driver

E-BEAM
DUMP

1.5 m

40 m

INJECTOR

60 SNOMAD-IV MODULES

FEL WIGGLER MAGNET

RADIATION
BEAM
GUIDE

120 m

SCIENCE RESEARCH LABORATORY

C-7

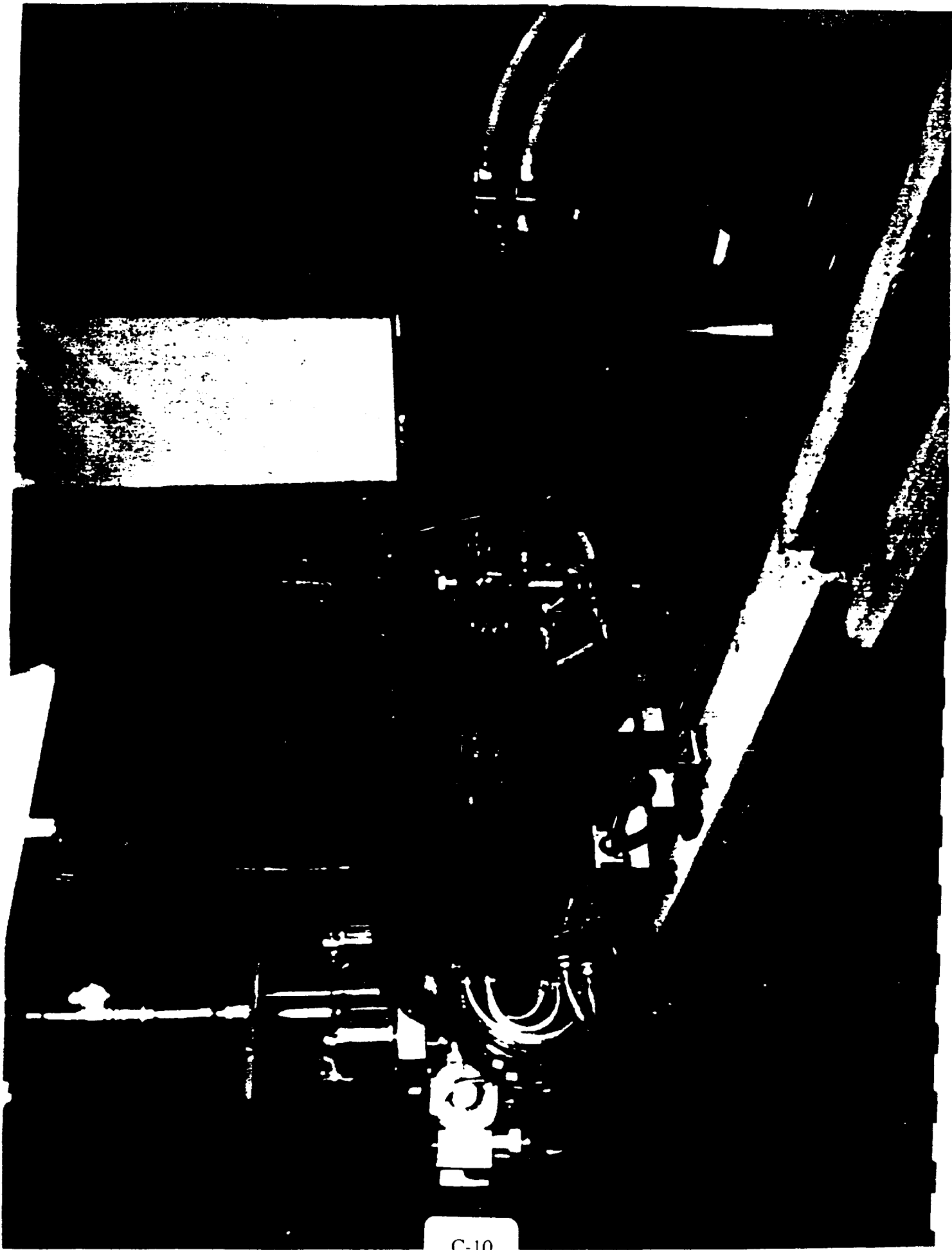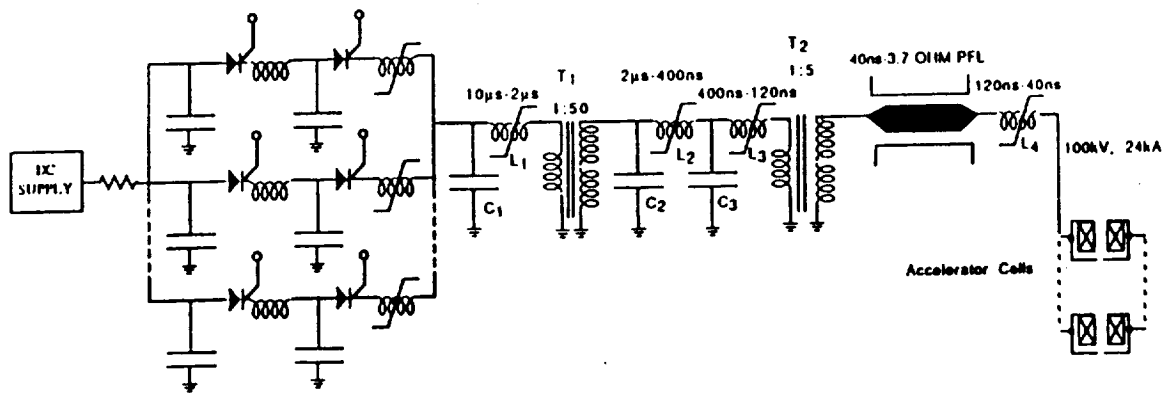# FEL Design Parameters

- Radiation Wavelength $\lambda = 1\ \mu\text{m}$

- Average Radiated Power $\overline{P} = 10\ \text{MW}$

- Peak Radiated Power $P = 10\ \text{GW}$

- Wiggler Wavelength $\lambda_w = 4\ \text{cm}$

- Normalized Wiggler Magnetic Field $a_w = 1.2$

- Wiggler Length $L = 40\ \text{m}$

- Wiggler Design   Hybrid permanent magnet / electromagnetic wiggler

C-10

DC SUPPLY

10μs-2μs T_1 1:50 L_1 C_1

2μs-400ns 400ns-120ns L_2 C_2 C_3 L_3

T_2 1:5

40ns-3.7 OHM PFL 120ns-40ns L_4 100kV, 24kA

Accelerator Cells

- Nonlinear saturable inductors
- 400 VDC converted to 100 kV, 50 ns pulses
- High (20 kHz) repetition rate

SNOMAD ACCELERATOR SPECIFICATIONS

	SNOMAD-IV	SNOMAD-V
• Energy/Module	1 MeV	3 MeV
• Acceleration Gradient	1 MeV/m	3 MeV/m
• Current	800 Amps	1 kA
• Pulse Flattop	70 ns	7 ns
• Repetition Rate	10 kHz	20 kHz
• Design goal	optimum $/Watt	minimum $/volt

SNOMAD-II VOLTAGE AND CURRENT WAVEFORMS
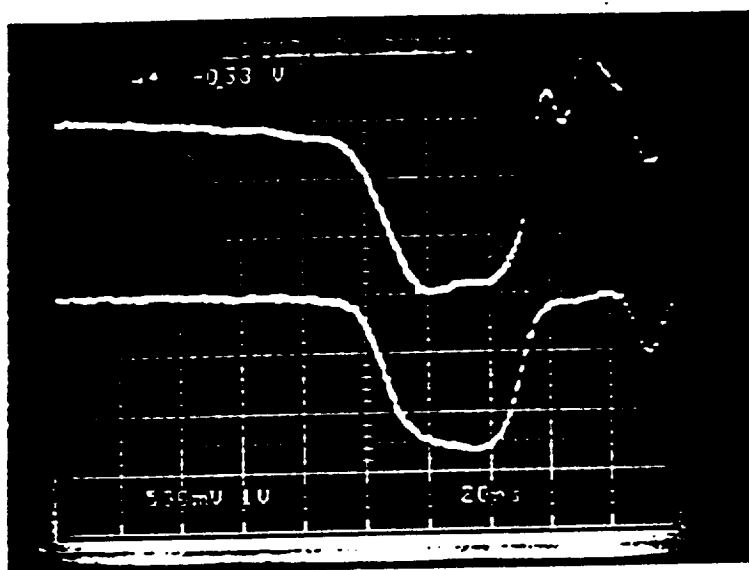
Voltage
(200 kV/div)

Current
(200 A/div)

- **Present injector has achieved necessary voltage and current.**

SNOMAD-II TECHNOLOGY DEMONSTRATION
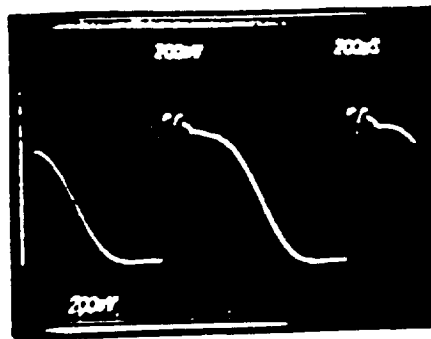
200 microseconds/div
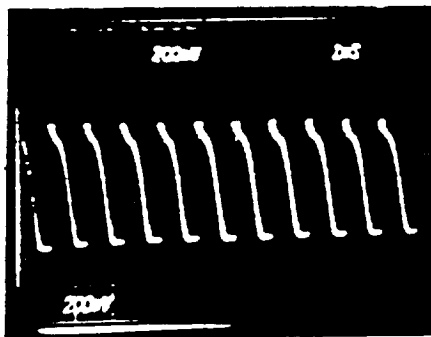
1 msec/div
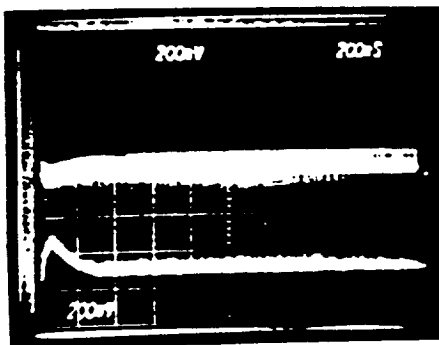
200 msec/div

- 1 kHz continuous operation
- Pulse power technology similar to proposed SNOMAD-IV based accelerator

SCIENCE RESEARCH LABORATORY

C-13

PREDICTED SENSITIVITY TO VOLTAGE VARIATIONS DURING PULSE
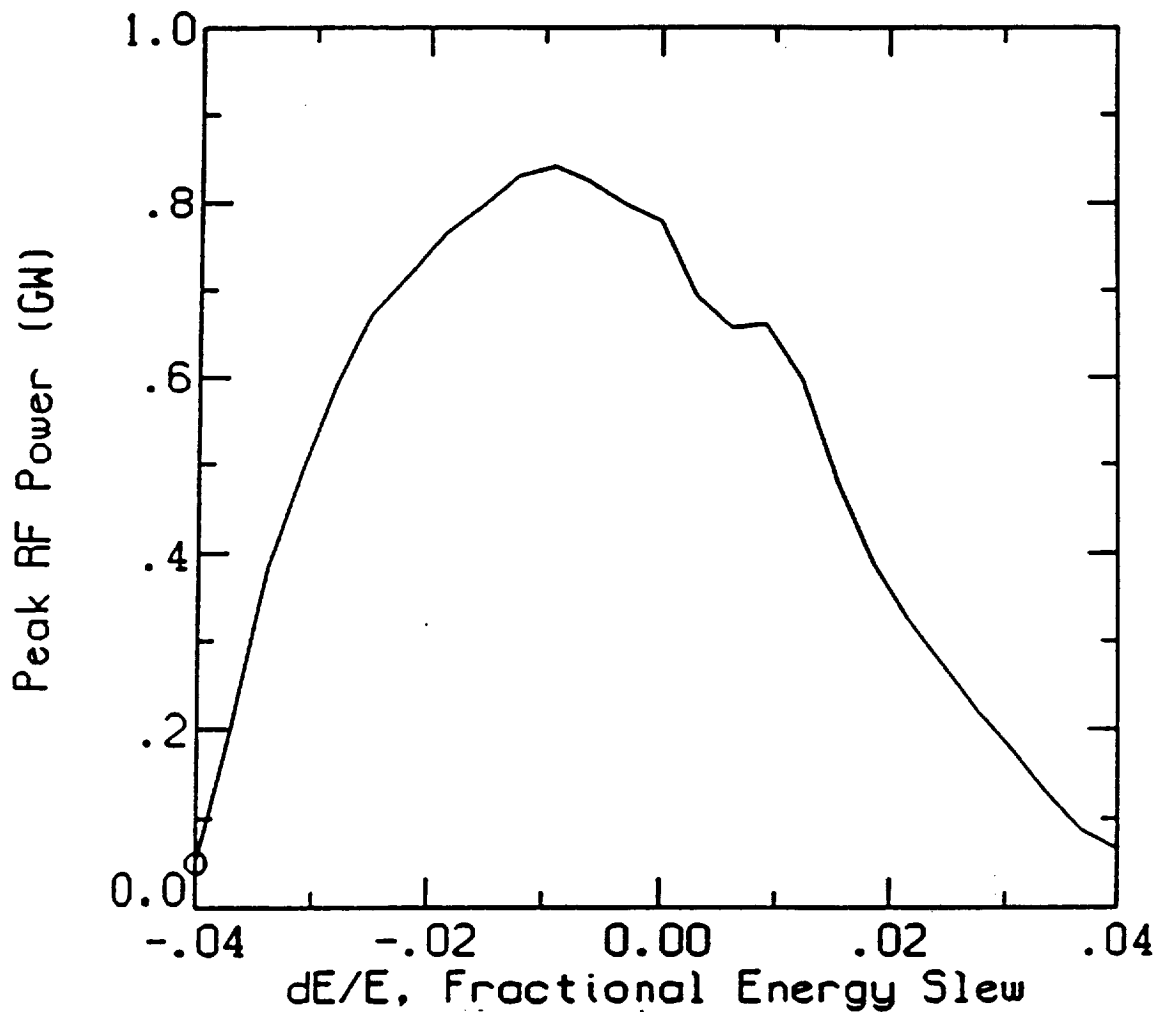
- **FRED** [†] **calculation shows that ±1.5% variation is acceptable.**

† Courtesy of H. Shays/LLNL

SCIENCE RESEARCH LABORATORY

ACCELERATOR DESIGN ISSUES

- Output Voltage Flatness

- Minimization of Number of Betatron Wavelengths
  to Reduce Cork Screwing

- Beam Break-up

- Timing Jitter

- High Repetition Rate Operation (Fast Resets,
  Oscillation Damping)

- Bussing Design (Individual Coaxial Lines,
  Ferrite Isolators)

- Most of these issues will be resolved in the first year of the proposed program

SCIENCE RESEARCH LABORATORY

PROGRAM STATUS

	SNOMAD-IV	SNOMAD-V
- Beam Energy	500 keV	1 MeV
- Beam Current	1 kA	1 kA
- Pulse Duration	50 nsec	5 nsec
- Repetition Rate	10 kHz	20 kHz
- Accelerator Gradient	0.7 MeV/m	2 MeV/m

SCIENCE RESEARCH LABORATORY

PROGRAM STATUS

- Focus on all-solid-state SNOMAD IV technology
  - lower risk
  - lower cost/Watt

- PHASE I (FY 1991)
  - Fabricate and test 1 MeV accelerator module (1.5 MeV total beam energy)
    Measure - Duration of flat-top beam
            - Beam emittance
  - Design wiggler

- PHASE II (FY 1992)
  - Extend beam energy to 6.5 MeV by fabricating 5 additional modules
    Measure - Beam emittance and beam instability growth rate
  - Perform wiggler design verification tests

- PHASE III (FY 1993-5)
  - Fabricate 50-100 MeV induction accelerator and wiggler

CONCLUSIONS

1. Induction Linac Driver FEL $(\lambda \sim 1 \, \mu m)$
   - High (1 - 10 MW) average power possible
   - Beam quality (emittance, voltage flattop) needs improvement

2. Several design goals already achieved
   - High repetition rate
   - Low cost
   - Reliable ($> 10^{11}$ shot life)

3. Program addresses design issues
   - Beam emittance and energy spread reduction by injector geometry design and feedback control

PAMELA

(PHASED ARRAY MIRROR, EXTENSIBLE LARGE APERTURE)

LIGHTWEIGHT OPTICS USING
SEGMENTED PRIMARY MIRROR

TECHNOLOGY WORKSHOP
ON LASER BEAMED POWER

NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO

5 February 1991

Greg Ames
Kaman Sciences Corporation

KAMAN

BACKGROUND REVIEW

The origins of the work to be presented here may be traced to an internally funded development within the KAMAN Diversified Technologies Group which took place in 1986. This work was initiated and directed by Dr. John Rather and it successfully resulted in the completion of top-down system level trade studies and the definition of a new approach to designing and building large aperture telescopes. It became known as the PAMELA™ concept, which is an anacronym for a Phased Array Mirror Extendable to Large Apertures.

As part of this work we set about identifying the necessary technologies which make this a feasible concept. Where necessary, as in the case of the edge sensors to be discussed here, we even proceeded to invent new technology bases to insure that the concept would be capable of attaining all of the quantitative and qualitative goals we had set. Where appropriate, we also conducted proof-of-concept tests to assure ourselves that we were indeed on the right track. By mid August of 1986 we had advanced the PAMELA™ concept to a sufficient level of maturity to begin sharing our results with interested parties within the government.

Several patents were filed as a direct result of this effort and by 1989 we had been awarded patents on each of the three topics listed: the PAMELA™ system architecture; the edge sensors; and an electromagnetic actuator. Only the edge sensors will be discussed in any detail here.

By July of 1989 KAMAN received its first contract to produce a working subscale demonstrator for the PAMELA™ concept. This concept was awarded through the U. S. Army Strategic Defense Command and is jointly funded by both DARPA and the SDIO. It is a three phase program and we are currently nearing the middle of Phase II. As a result of this contract we have made significant advances in the state of the edge sensor technology. It is our hope that by presenting these results here today we will provide the architects of large optical systems with yet another useful advancement in the state of technology.

D-1

BACKGROUND REVIEW

1986 KAMAN DEVELOPS PAMELA™ CONCEPT

- **System Level Trade-Off Studies Completed**
- **Identify/Invent Enabling Technologies**
- **First Proof-Of-Concept Tests Conducted**

1989 PATENTS AWARDED

- **PAMELA™ System Architecture**
- **Edge Sensors**
- **Actuators**
- **Wavefront Sensors**

1989 FIRST CONTRACT AWARDED THROUGH THE U.S. ARMY STRATEGIC DEFENSE COMMAND

- **Funded by DARPA, SDIO**
- **Three Phase Program**
- **Technology Demonstration**

PAMELA   **KAMAN**

PHASE I TEST CONFIGURATION

In order to actually demonstrate the ability of the edge sensors to be used to phase match two segments we attached one sensor pair to a set of segments and configured them for testing as shown. With this set-up we were able to demonstrate closed-loop edge matching at a bandwidth of 100 Hz.

PROGRAM OVERVIEW

PHASE 1 GOAL
- Demonstrate closed loop control of the common edge between two segments at λ/20 rms (λ = 632.8 nm)
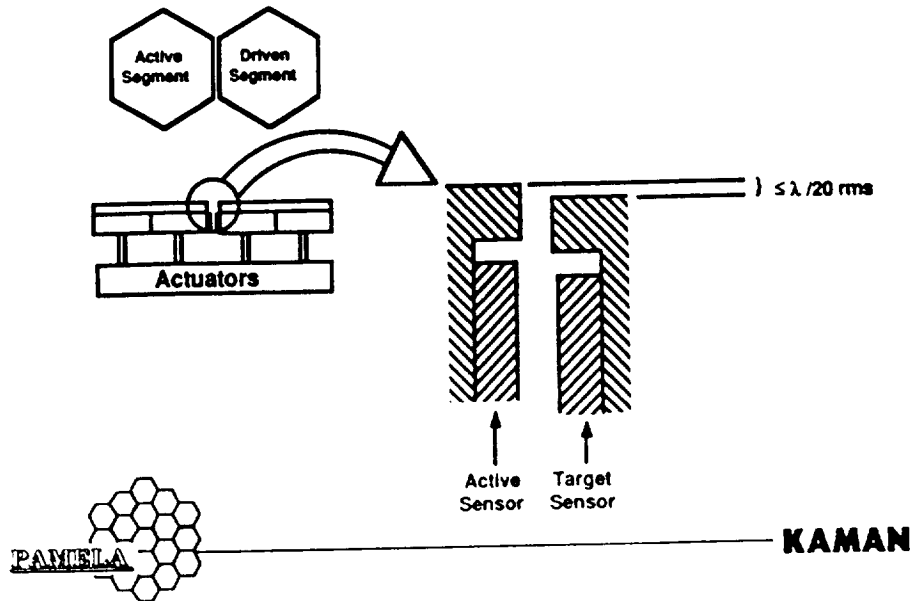
PROGRAM OVERVIEW

PHASE 2 GOAL
- Demonstrate λ/20 control on all edges of a segment while simultaneously sensing and controlling its tilt
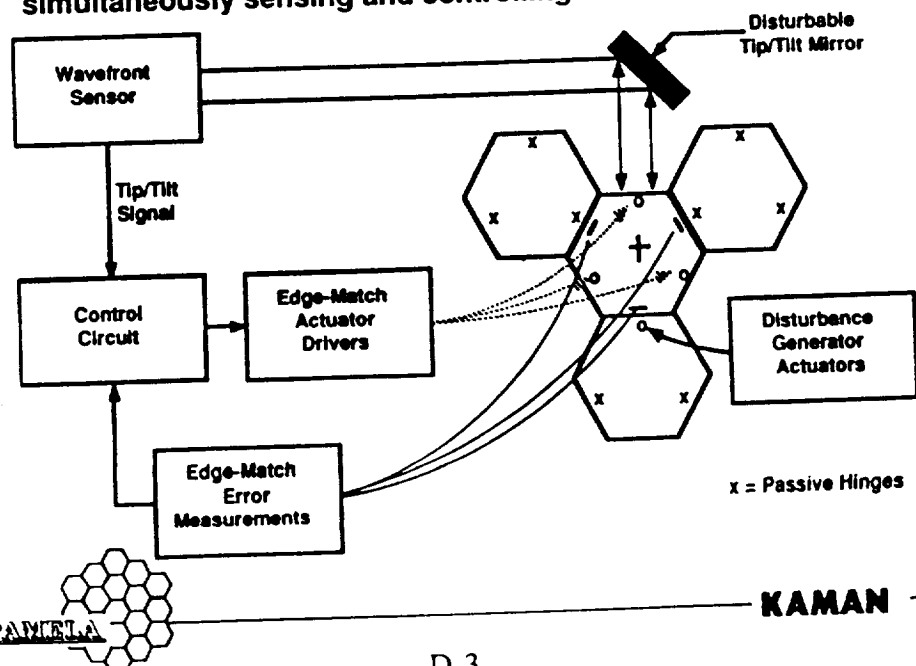
PROGRAM OVERVIEW

PHASE 3 GOAL

- Fabricate a 36 segment demonstrator that will:

  - Produce diffraction limited illuminated target images in the presence of:
    - atmospheric turbulence
    - thermal deformations
    - large scale optic fabrication errors
    - optic misalignments

  - Stabilize target images (remove tracking jitter)

  - Demonstrate rapid retargeting within the instantaneous field of view

  - Transmit a diffraction-limited laser beam to produce airy disk on target

PAMELA — KAMAN

PAMELA DEMONSTRATOR SCHEMATIC DIAGRAM

SEGMENT CONTROLLER

HOST COMPUTER

RETROFLECTOR

SHUTTER

COARSE/FINE WAVEFRONT GRADIENT SENSOR

SECONDARY MIRROR

PUPIL RELAY OPTICS

BEAMSPLITTER

SEGMENTED SPHERICAL PRIMARY MIRROR

LASER

INTENSIFIED CCD CAMERA

PAMELA — KAMAN

D-4
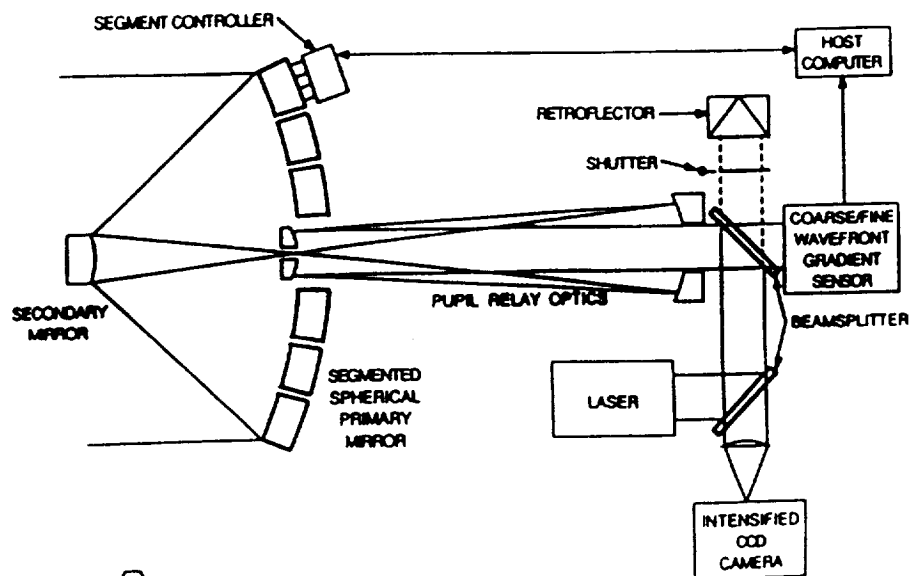
MIRROR AREAL MASS DENSITIES AS A FUNCTION OF SIZE

MIRROR AREAL MASS DENSITIES AS A FUNCTION OF SEGMENTSIZE
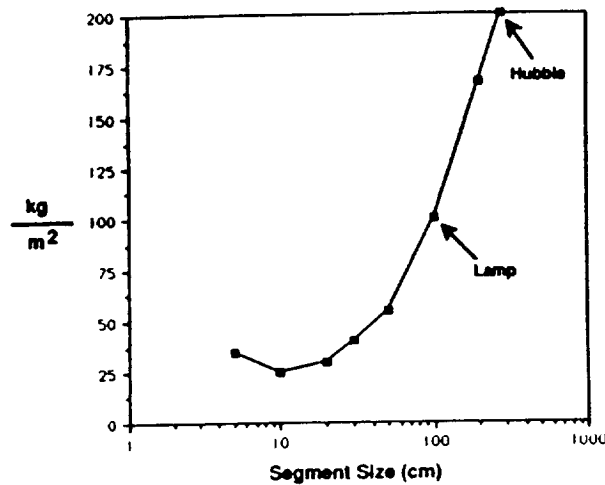
PAMELA   KAMAN

SEGMENT DESIGN GOALS REVIEW

SIZE	7 cm flat-to-flat hexagon, .82 cm thick
WEIGHT	≤ 1 oz.
MATERIAL	Silicon Carbide
STIFFNESS	1st Resonance ≥ 5 kHz

SURFACE

Figure:	Flat, ≤ 1/80 wave rms
Roughness:	≤ 25 Angstroms
Finish:	40-20 scratch-dig
Coating:	Metallic film, ≥98%R, Broadband Visible, Protective Overcoating

COST TARGET $5.9K (tooling) + $2.9K (substrate) + $2.4K (coating)

KAMAN
AEROSPACE CORPORATION

EDGE SENSORS

D-6   **KAMAN**
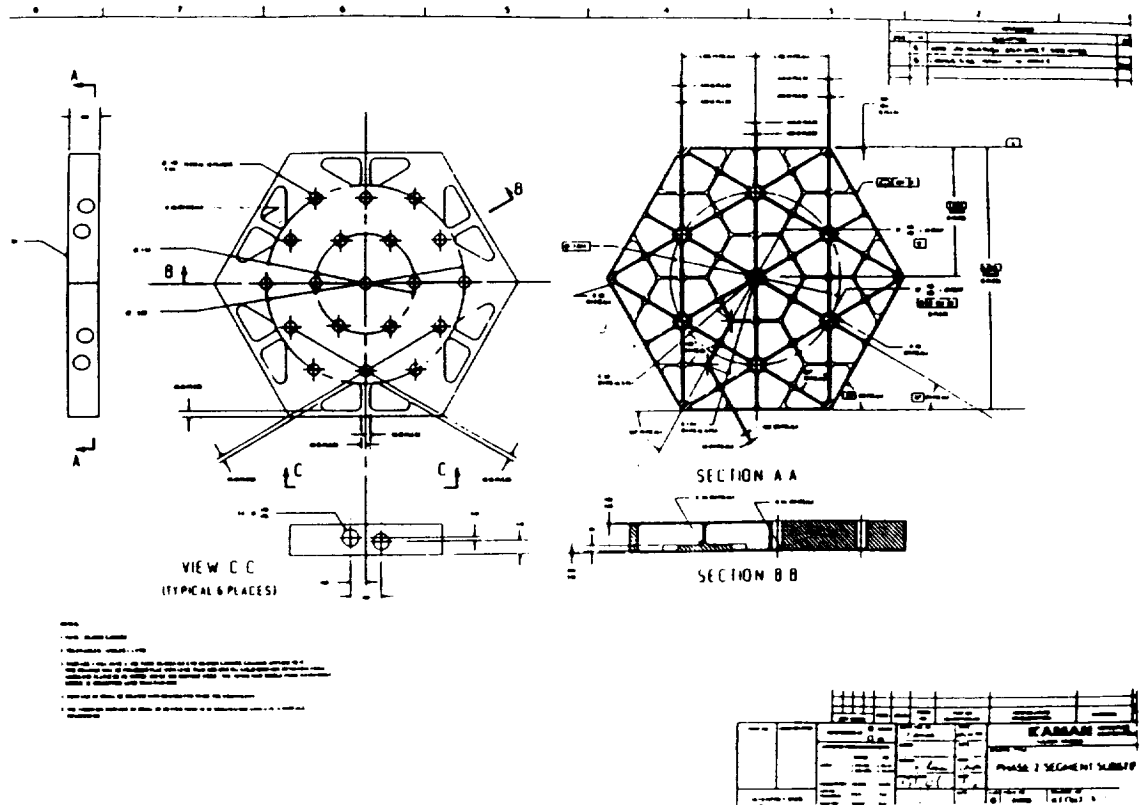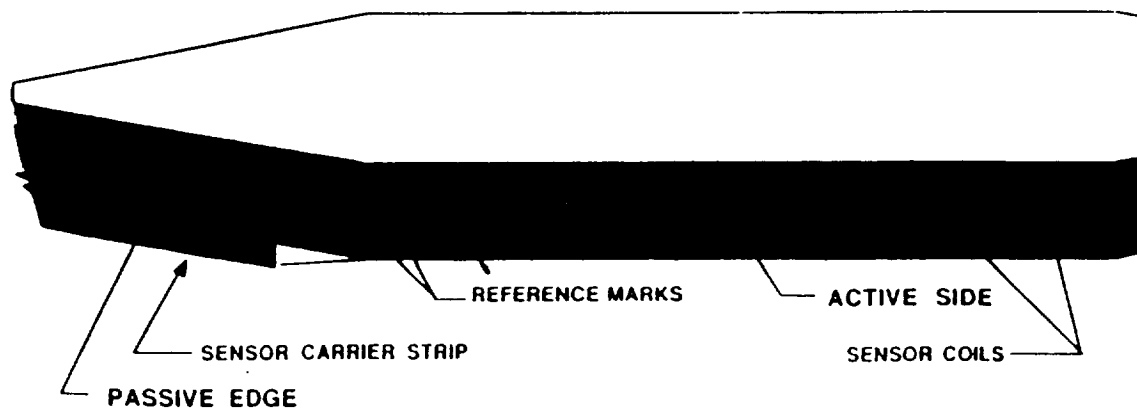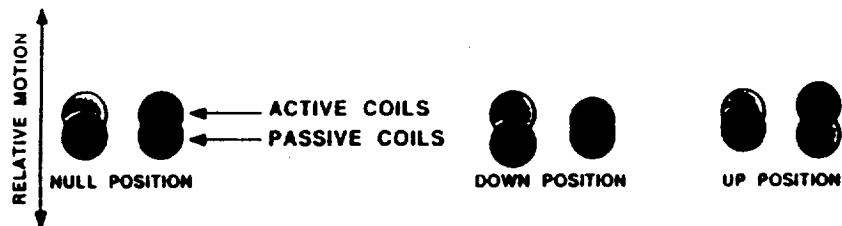
CONVENTIONAL APPROACH

Previous researchers had employed various schemes to insure edge matching of optical segments. By far the most typical approach is depicted here. As shown, a dimensionally stable material such as ULE is used to form a cantilevered 'target paddle' which bridges the gap between segments. Often a pair of sensing elements is used in a differential pair arrangements to sense the motions of the target paddle which are normal to the front surface of the mirror. Both inductive and capacitive sensing technologies have been successfully employed for this purpose.

This arrangement presented several unacceptable disadvantages for the PAMELA system. First, it added mass to the segments, and we were working toward a solution which necessitated large numbers of small, light weight, and inexpensive segments. The mass of the cantilever relative to the segment mass would be unacceptably high for segment sizes of interest to us.

Secondly, we were seeking a system architecture which could be utilized for high energy beam directors. Protecting the cantilever from the energy leaking through the gaps would further complicate the utilization of this approach to edge sensing. Likewise, the difficulties of installing large numbers of interlocking segments/sensors was sufficient to cause us to seek other approaches.

Finally, this technique relies too heavily on the mechanical stability of two non-symmetrical structures.

CONVENTIONAL APPROACH

Mirrored Surface

Segment   Segment

DISADVANTAGES:

- Added mass of cantilever

- Cantilever subject to thermally induced distortions

- Installation is complicated significantly for large numbers of small segments

- Measurement point is somewhat removed from condition being controlled

Differential Sensors

Cantilevered 'Target Paddel'
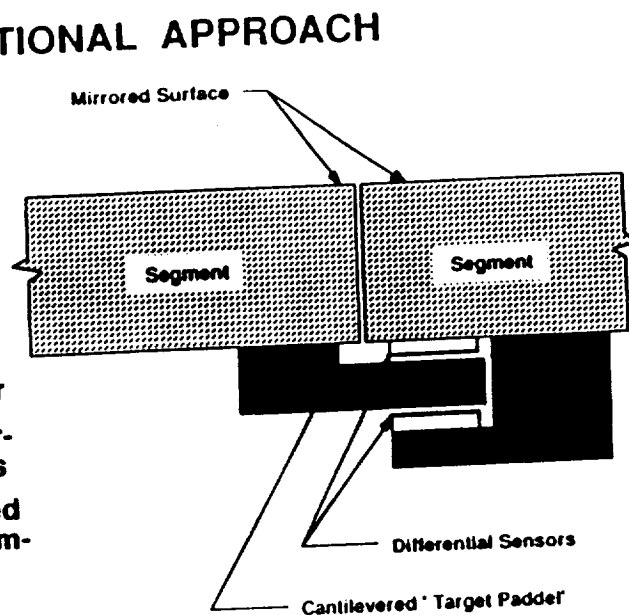
KAMAN

Previous system level studies had established certain qualitative requirements for the segment edge matching sensors such as ease of use and assembly, economy and reliability, "in the gap" measurement as close to the front surface as possible, and noncontacting. Key performance issues were also addressed. In particular, these sensors would be required to measure the piston errors to a high degree of accuracy at high bandwidths. Estimates of bandwidth requirements as high as 27 kHz grew out of our need for an edge sensor which introduced minimum phase shift to the nested control loops which will be required.

After establishing that there were no commercially available transducers which met these needs, we embarked upon an internally funded research and development program to develop one. This resulted in KAMAN's patented edge sensors which were specifically invented to fill this need.

KAMAN'S SOLUTION

Mirrored Surface

Segment   Segment
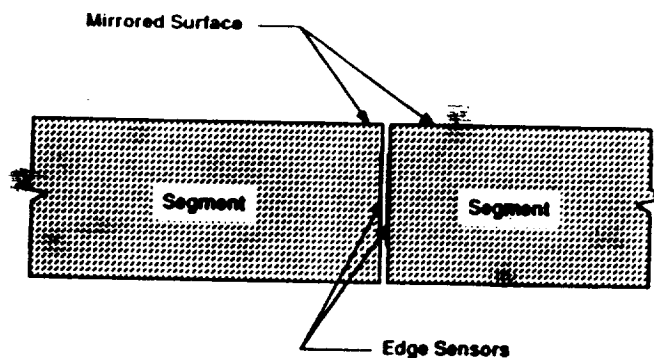
Edge Sensors

Inductive, variable coupling type

Absolute, self-referencing

No contact, no connections across gap

Sensors attached directly to edges

High bandwidth (>20k Hz)

Wide dynamic range (>95 dB)

KAMAN

D-8

FUNCTIONAL SCHEMATIC

Series resonant primary coils on the "active edge" of one segment inductively couple to two tuned secondary coils on the "passive edge" of the adjacent segment. One passive coil is tuned slightly above resonance and the other slightly below resonance. Any relative motion between the edges causes a change in the complex impedance of the primary which in turn produces a change in the phase relationship between current and voltage. This phase change, used to produce a control signal for the actuators, is linearly related to the relative motion between the segment edges.

The tuned secondary coils are completely passive, thus no wires need bridge the gap between edges. The null point is defined by the plane of symmetry where the primary equally couples with both halves of the secondary, thus the null point should be insensitive to changes in gap separation or temperature. Since the secondary can be tuned, it can be made both extremely sensitive and linear.

FUNCTIONAL SCHEMATIC

Passive Side

Z1   Z2

L_1 L_2

Direction of Travel

L_3 L_4 Active Side

Synchronous Demodulator

V_{out}

Passive Coils

Active Coils

Direction of Travel

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D-9
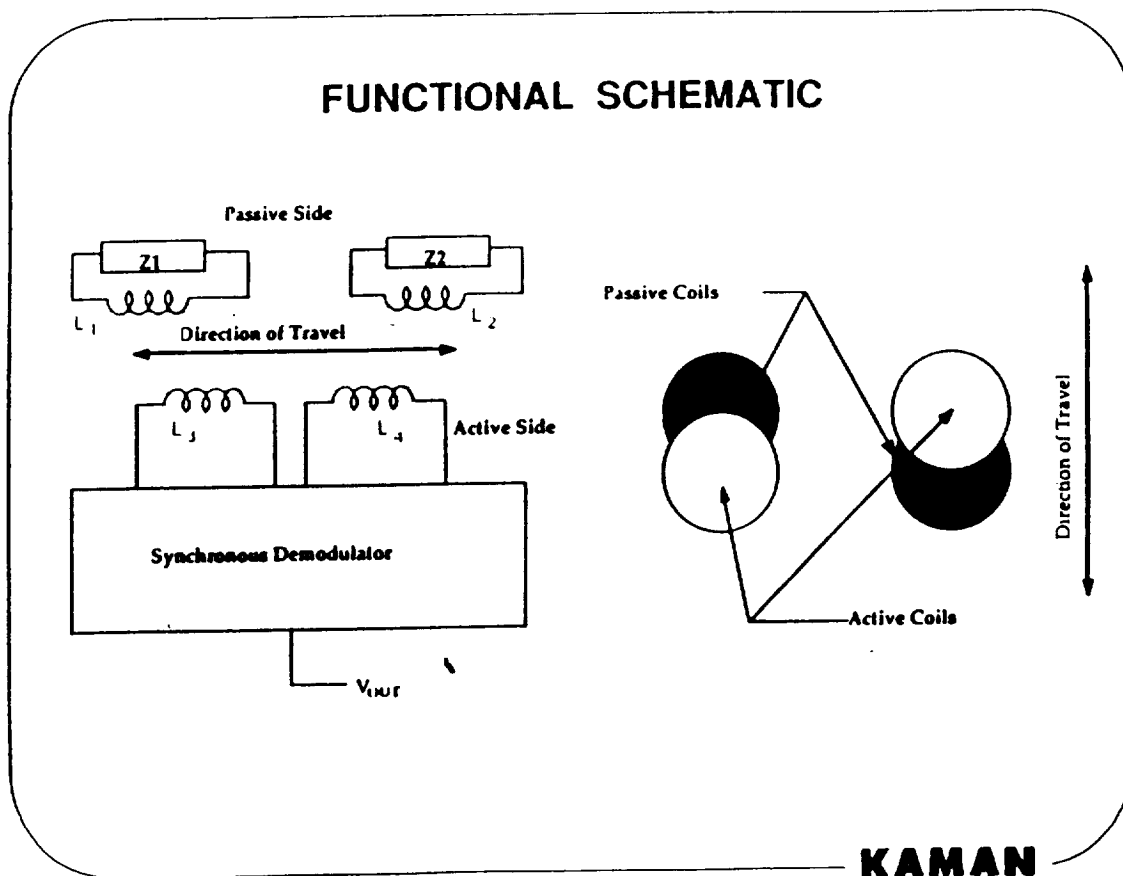
DESIGN GOALS

The specific performance goals for the edge sensors were established at the outset and are summarized here.

The minimum range requirement is really the capture range of the sensor and is largely driven by the gross edge matching errors present in the initial unpowered array at turn-on. This requirement is mainly a reflection of the expected manufacturing tolerances of the support structure and actuator/segment assemblies.

Nominal gap was established primarily as a matter of practical convenience for Phase I. Resolution and accuracy requirements speak for themselves. Both are broadband requirements. The accuracy requirement results from our need to achieve $\lambda/20$ edge matching at $\lambda=632$ nm. This accuracy requirement was to include temperature variations of $\pm10°C$.

We decide to roll off the frequency response of the sensor at 10 kHz, since our closed loop bandwidth for this phase of the development was on the order of a few hundred hertz. At this time we do not know of any limiting phenomena which will prevent us from opening up the sensor frequency response to 30 kHz by simply changing the corner frequency of the output filter.

Since we were working with segments of a given size, the edge sensors had to be small enough to fit on the edges. We felt that this was about as small as we could go without introducing significant coil placement inaccuracies at this time.

A specific design goal is to achieve our performance requirement with fairly low complexity electronics. This is because we ultimately plan to incorporate the entire signal conditioning circuit for the edge sensors on a single IC. Our philosophy is that it is easier to start simple and add complexity where needed than it is to go the other way.

DESIGN GOALS

- **PERFORMANCE REQUIREMENTS:**

Minimum Range	±200 μm
Nominal Gap	254 μm
Resolution	<20 nm rms
Accuracy	<30 nm rms
Bandwidth	>10 kHz

- **PHYSICAL REQUIREMENTS:**

  Small enough to fit on the edges of 8 mm
   thick segments

  One sensor site per edge

  Low complexity signal conditioning

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TRANSFER FUNCTION

Here we see the full scale transfer function of the edge sensors. In this chart, the scale factor is decreasing as the gap is increased form 50 to 500 μm. The vertical scale, which is in units of VDC, represents the signal level before the gain and offset and final output filter stages of the signal conditioning circuits. So it is evident that the sensor required very little electronic gain in order to achieve the 10 mV/μm output scalefactor.

Note that in the region near 0 displacement the edge sensor appears to be insensitive to changes in gap. Careful analysis of the data indicates that indeed for a given gap we can tune the edge sensors for minimum sensitivity to gap changes. (Less than 25 nm for a 14 μm change in gap dimension.) Furthermore, we can tune this point to coincide with the position at which the front surfaces of the segments are precisely phase matched. This is the region we refer to as the null point.

SENSOR TRANSFER FUNCTION

Sensor output voltage vs. edge mismatch in micrometers.
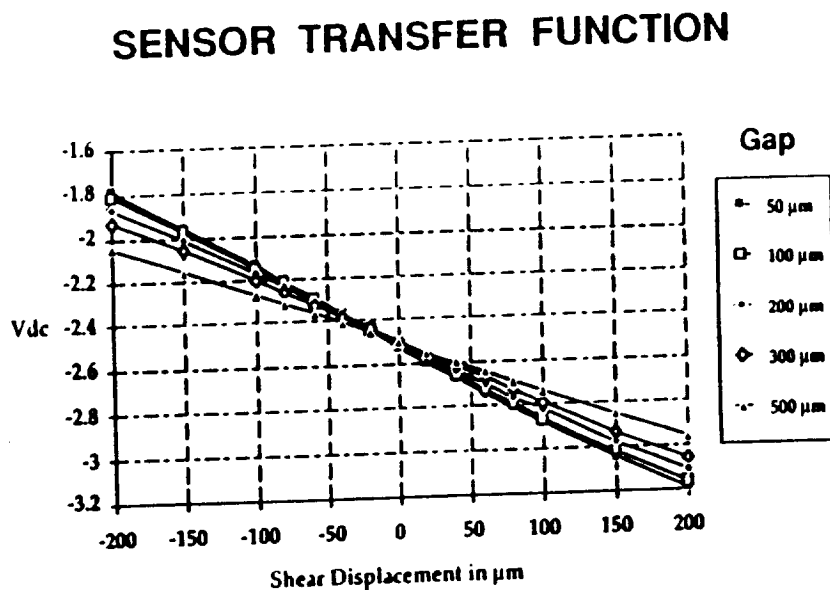
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This table presents a summary of the performance parameters which were verified in Phase I. First, note that we have considerably greater usable range than we need. This is largely a function of the coil size. This gives us confidence that we will achieve equal or better performance in Phase II when we go to smaller sensing coils necessitated by the thinner segments we expect to be using.

The gap specified is just a reflection of recommended operating condition. There is really no reason that the sensor can not be operated at even smaller gaps except for the practical difficulties associated with testing and installation. As we progress to smaller coils, we will also most likely try to work at a gap dimension of 50 to 100 μm. This should have a positive impact on resolution and accuracy.

Scale factor and noise performance are both satisfactory, but the null stability vs. temperature is a big concern at this time. We were surprised to see this number so high since our initial analyses had led us to believe that the sensor should respond to temperature changes in much the same way that it responds to gap changes as seen in figure 3.1.4. Unfortunately the problem really only became clearly evident rather late in the program and we were unsuccessful in our efforts to compensate for the effect in the time remaining.

In recent weeks we have made considerable progress in developing a comprehensive computer model which so far has substantiated our initial expectations. That is, the sensor should be insensitive to temperature changes over some region of operation and that region may be made to coincide with our desired operating point or null point as we call it. More work is need on this computer model before we can be absolutely certain that these predictions are accurate however.

PERFORMANCE SUMMARY

PARAMETER	CONDITION	MIN.	TYP.	MAX.	UNITS
Range			±200	±1500	μm
Gap		100	200	300	μm
Linearity Error			0.7	2	% of Full Range
Scale Factor	no amplification		3.2		mV/μm
Noise	B.W. = 0 to 10 kHz			20	nm peak-to-peak
Gain Stability					
vs. Time				20	ppm/hr •••
vs. Temperature	65 °F ≤ T ≤ 95 °F			0.02	%/°C •••
Null Stability					
vs. Time	over 18 hours			15	nm rms
vs. Temperature	10 °C ≤ T ≤ 44 °C			40	nm/°C
Gap Sensitivity	Gap=200±5 μm				
Null Point Shift	ΔGap ≤ 14 μm			25	nm
Slope Shift	ΔGap= ±100 μm		-0.1		%/μm
Null Adjustment	@Gap=constant		3		μm

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EDGE SENSOR: COIL INSTALLATION COMPLETE

PAMELA   KAMAN

ACTUATOR REQUIREMENTS

- LONG STROKE ($\geq$ 150 μm) REQUIRED FOR LARGE GROUND-BASED MIRRORS TO COMPENSATE ATMOSPHERIC TURBULENCE

- HIGH BANDWIDTH IS REQUIRED TO COMPENSATE ATMOSPHERIC TURBULENCE, ESPECIALLY FOR LOW EARTH ORBIT SATELLITE TARGETS ($\geq$ 3 kHz)

- PRECISION REQUIRED IS SMALL FRACTION OF OPERATING WAVELENGTH

- PUSH-PULL ELECTROMAGNETIC ACTUATORS CAN MEET STROKE, FORCE, AND BANDWIDTH REQUIREMENTS WITHOUT HYSTERESIS OR HIGH VOLTAGE

- DYNAMIC PERFORMANCE CAN BE IMPROVED BY INTEGRATING A POSITION SENSOR INTO EACH ACTUATOR ELEMENT SO THE SEGMENT CONTROLLER CAN DRIVE SEPARATE POSITION LOOPS

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ACTUATORS: TRADE-OFF STUDY
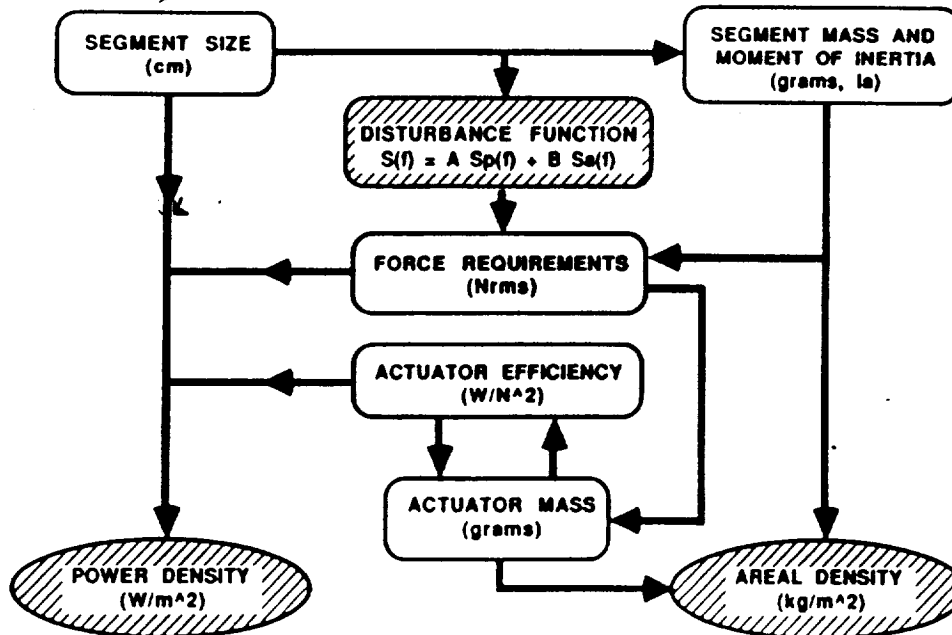
PARAMETERS SET BY SYSTEM REQUIREMENTS

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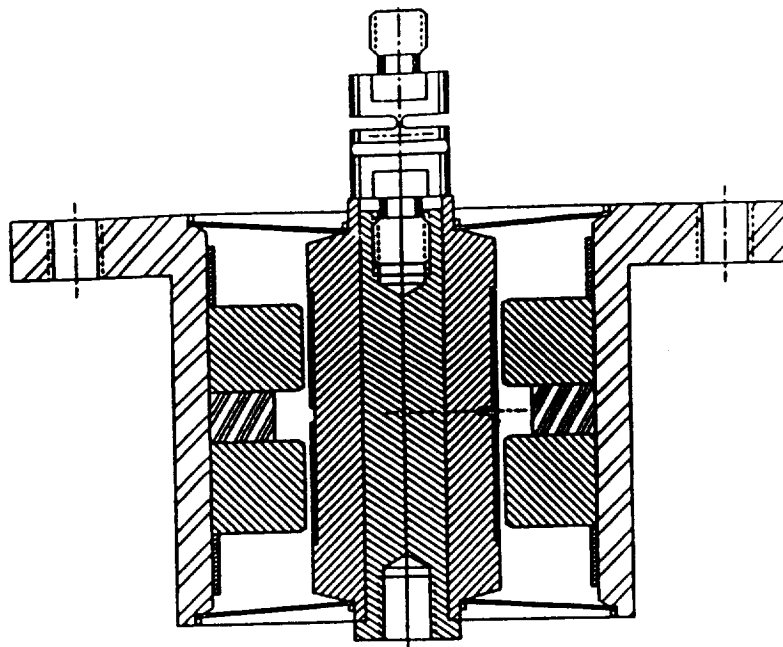
Cut-Away of Actuator

X=163. Hz
Ya=25.1539 dB
FREQ RESP   4Avg   0%Ovlp
40.0

dB

-40.0
Fxd Y 1   Log Hz

FREQ RESP   4Avg   0%Ovlp
80.0

Phase

Deg

-240
Fxd Y 1   Log Hz

D-15

ACTUATOR: MAGNET INSTALLATION

PAXETTA

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Coarse/Fine Wavefront Sensor Optical Layout
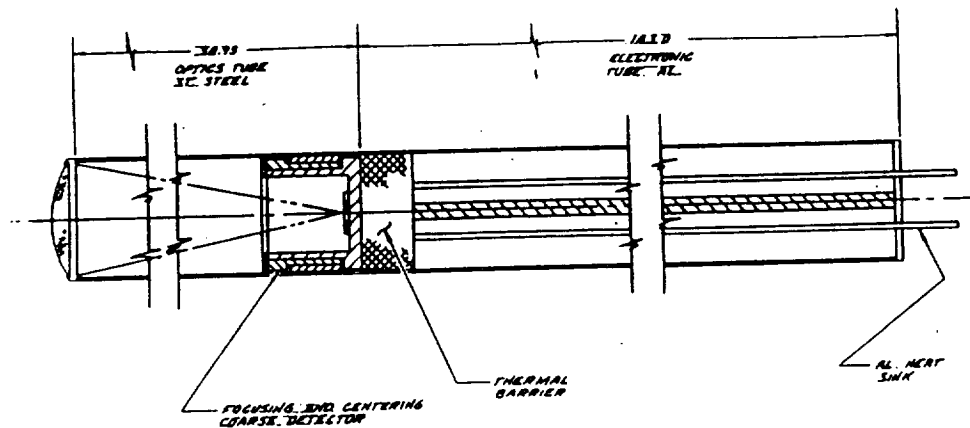
Hexagonal Subapertures (7 total) from Telescope

10 mm

Fine WFS arm →

focus

95.88   103.4 mm   60 mm

50/50 Beamsplitter

Coarse WFS arm

focus

quad cell

38 mm   0.93 mm

Ratio of Fine to Coarse Lever Arms
= 1.25 m/38.93mm
= 32.12

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COARSE WAVEFRONT SENSOR

OPTICS TUBE
ST. STEEL

ELECTRONIC
TUBE. AL.

THERMAL
BARRIER

FOCUSING AND CENTERING
COARSE DETECTOR

AL. HEAT
SINK

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OPTICAL TABLE LAYOUT

White
Light
Source

Spectral Notch
Filter (optional)

Reference Mirror

Compensator Plate

LDDM Head

Collimating Lens

Interferometer Flat

Optical Rail

Beamsplitter

WYKO 6000
Fizeau
Interferometer

Retroreflector

PAMELA
Segments

Screen

Camera

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1/30/90 DLB

D-17
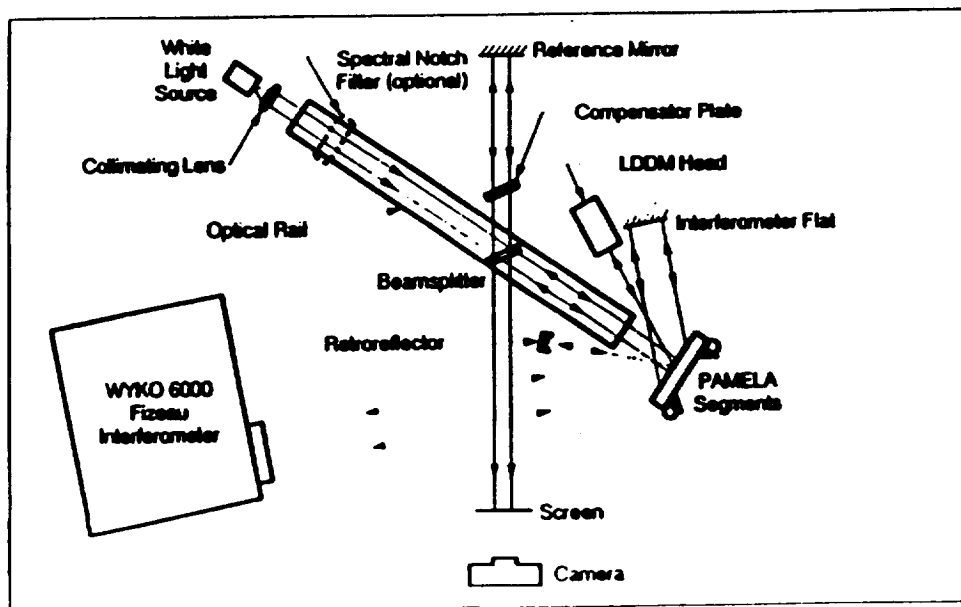
This figure shows the white light fringes which were used to find the initial zero piston error position between the segments. Note that the fringes are of different colors and that the central fringe (the darkest fringe in the picture) is almost completely colorless. This allows us to unambiguously determine which fringe is associated with a fringe on the opposite segment. The fringes shown in this picture are continuous across the gap which means that the segments are aligned at this time.

WHITE LIGHT FRINGES

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1/30/90DLB
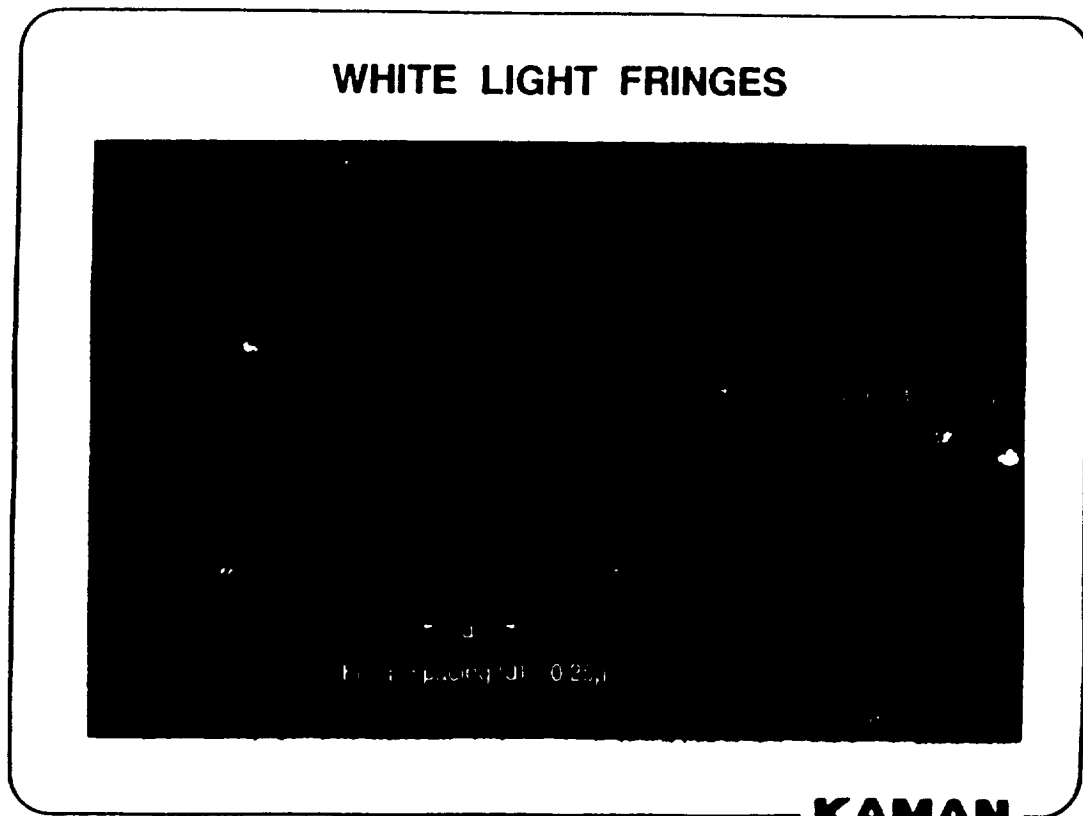
D-18

CONTROL SYSTEMS FOR ADAPTIVE OPTICS TECHNOLOGY

TECHNOLOGY WORKSHOP ON LASER BEAMED POWER

5 February 1991

Albert Lazzarini
Kaman Sciences Corporation

KAMAN

PRESENTATION OUTLINE

- Brief Overview of the Wavefront Control Experiment

- SDIO/AFSSD Program, part of Starlab Mission
- Membrane Deformable Mirror (Continuous Facesheet)
- Lateral Shearing Interferometer (Wavefront Sensor)
- Control Algorithms Appropriate to Membrane Mirrors

- Introduction to PAMELA

- SDIO/DARPA Program
- Segmented Optics (Sized to Appropriate r_0)
- Edge Sensors - plus - Segment Tilt Sensor
- Control Algorithms Appropriate To Segmented Optics

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WCE Missions

- Demonstrate use of adaptive optics to correct wavefront aberrations on incoming optical beam

- Demonstrate simultaneous optical wavefront correction and outgoing beam transmission

- Demonstrate hierarchical control

- Investigate image sharpening -
  a method to control a deformable mirror without a wavefront sensor

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STARLAB/WAVEFRONT CONTROL EXPERIMENT
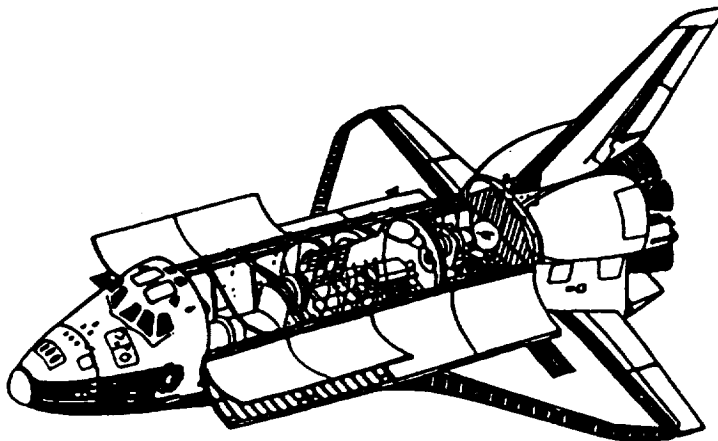
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ADAPTIVE OPTICS FUNCTIONS

OPTICAL ABERRATIONS

DIFFRACTION-LIMITED PERFORMANCE

MANUFACTURING ERRORS

MICROGRAVITY RELAXTION

COMPONENT MISALIGNMENT

DYNAMIC STRESS

THERMAL GRADIENTS

→ **ADAPTIVE OPTICS** →

SMALLEST TARGET IMAGE FOR BEST ATP

MAXIMUM MARKER/WEAPON IRRADIANCE ON TARGET

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Aerospace Corporation

Starlab   ELECTRO-OPTICAL SUBSYSTEM DESIGN

80 cm TELESCOPE

UV CAMERA

THERMAL CONTROL RADIATOR

ACQUISITION VIDEO

1.6-m POINTING MIRROR

DOUBLE SPACELAB MODULE

5-cm ILLUMINATOR BEAM

KAMAN EQUIPMENT

ESA PALLET

BEAM EXPANDER

TARGET CANISTERS

IR SENSOR

OPTICAL BENCH SUPPORT STRUCTURE

FOCAL PLANE ASSEMBLY

MARKER

OPTICAL BENCH

RACK 3 LMSC

RACK 5 KAMAN

KAMAN

E-3
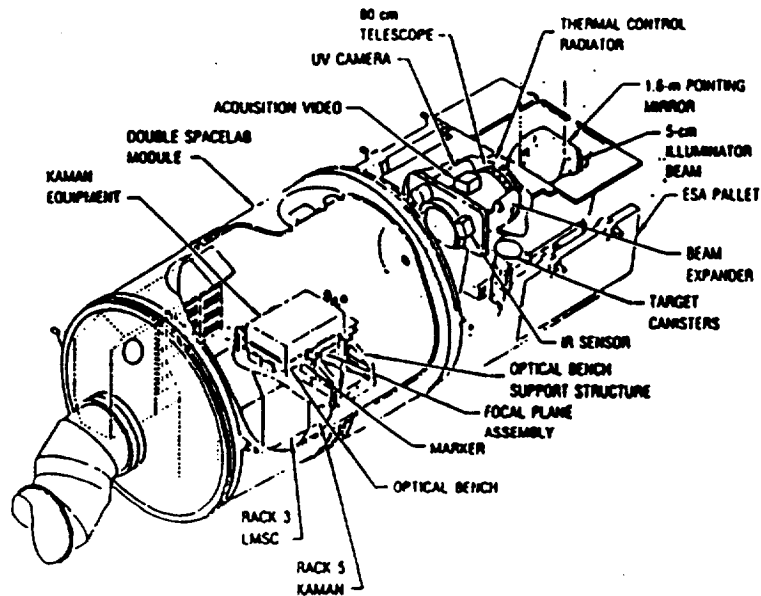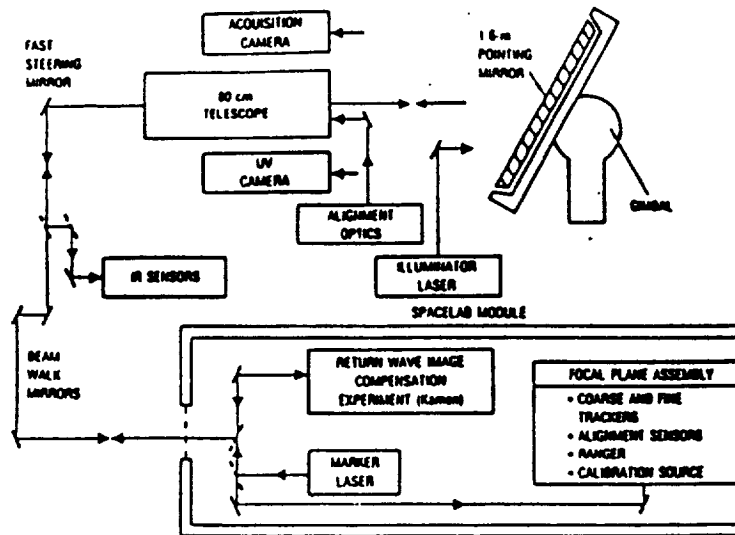
OPTICAL SCHEMATIC

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WCE OPTICAL LAYOUT

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E-4

STARLAB APERTURE EFFECIENCY
(STREHL·TRANSMISSION)
(HeNe)

Registration of WFS Subapertures
Relative to Piston Actuators on DM
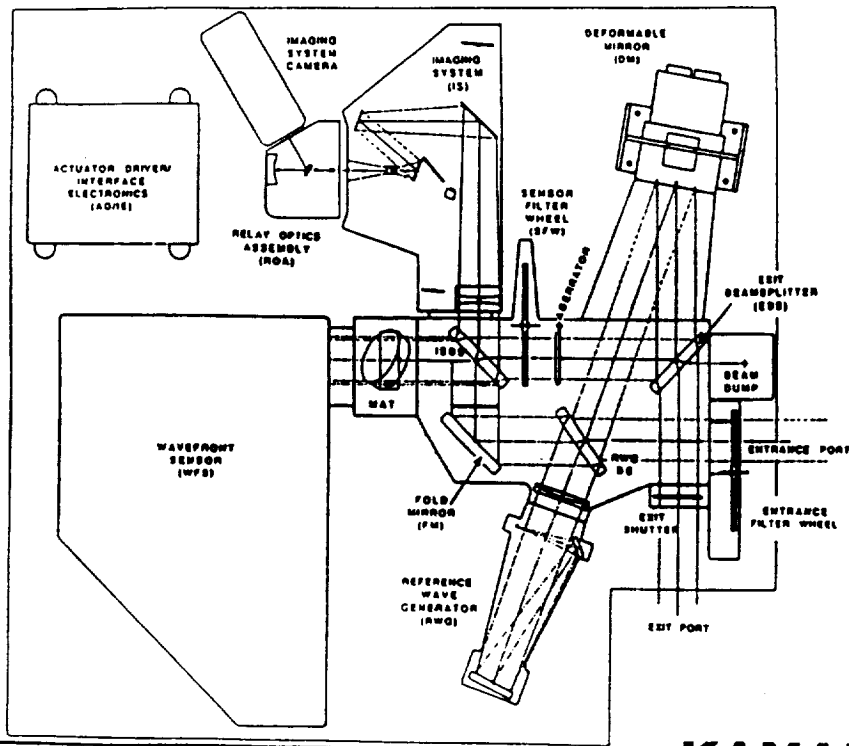
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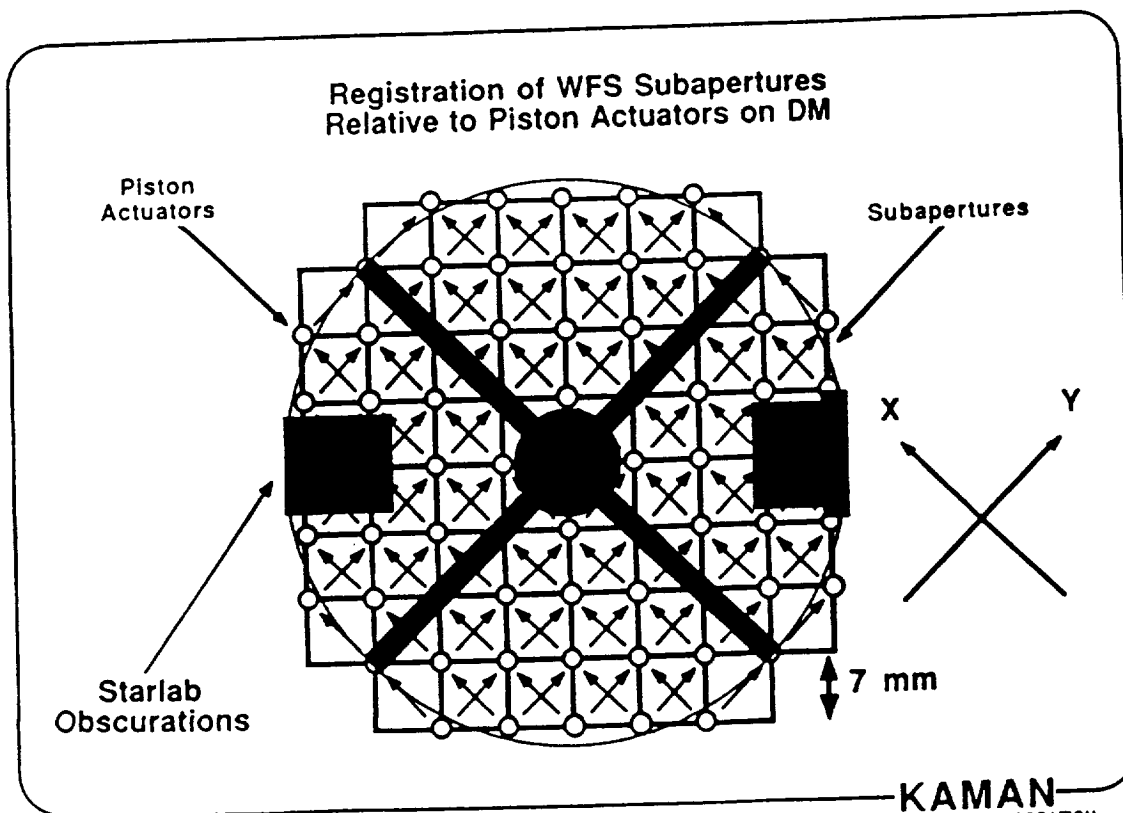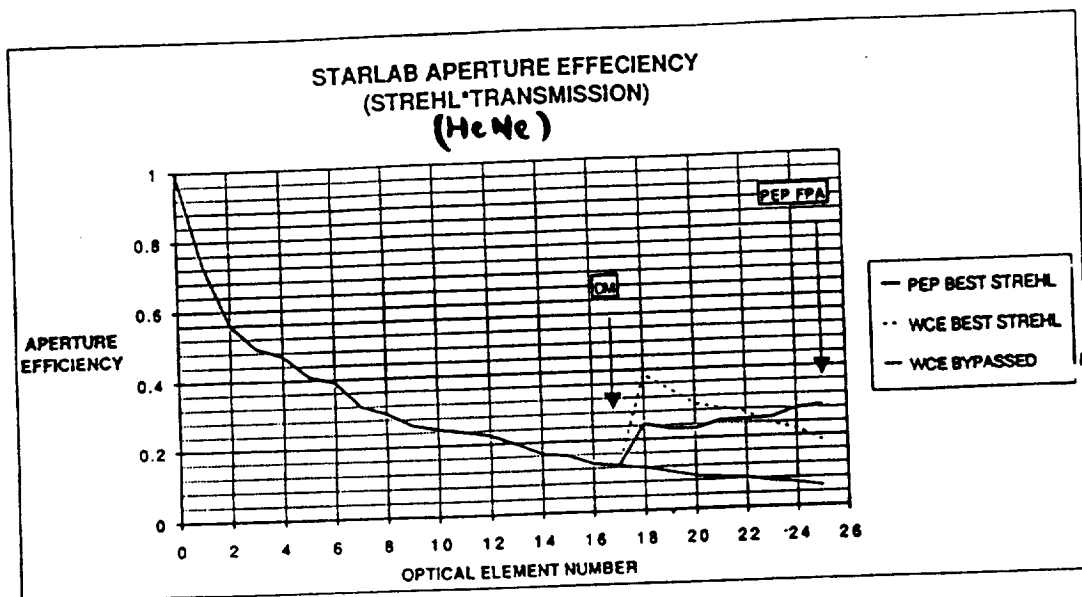
WCE Wavefront Sensor Schematic

LENSLET
ARRAY

FOLD MIRRORS

RELAY
OPTICS

ROTATING
GRATING

Field Stop
&
Capping
Shutter

PMT
ARRAY

INPUT
BEAM
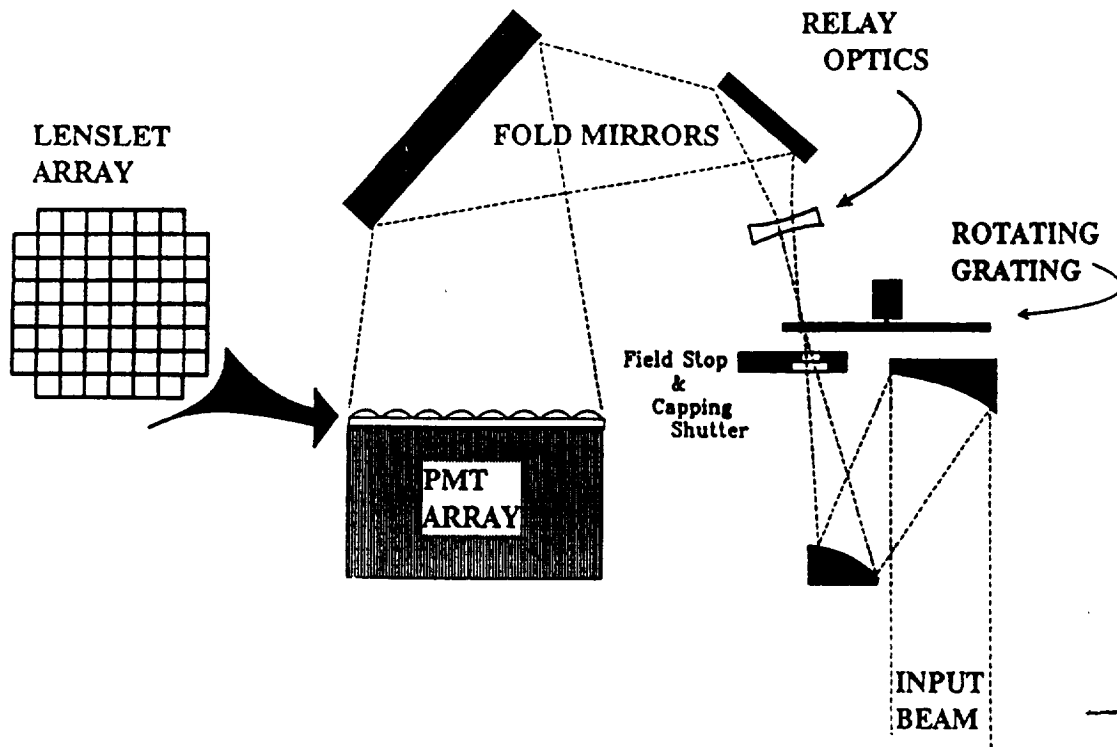
Principle of Rotating Grating Interferometer

Rotating
Radial
Grating

Perfect
Wavefront

Detector
Array

Relay
Lens

In-Phase
Signals

Distorted
Wavefront

Phase-shifted
Signals
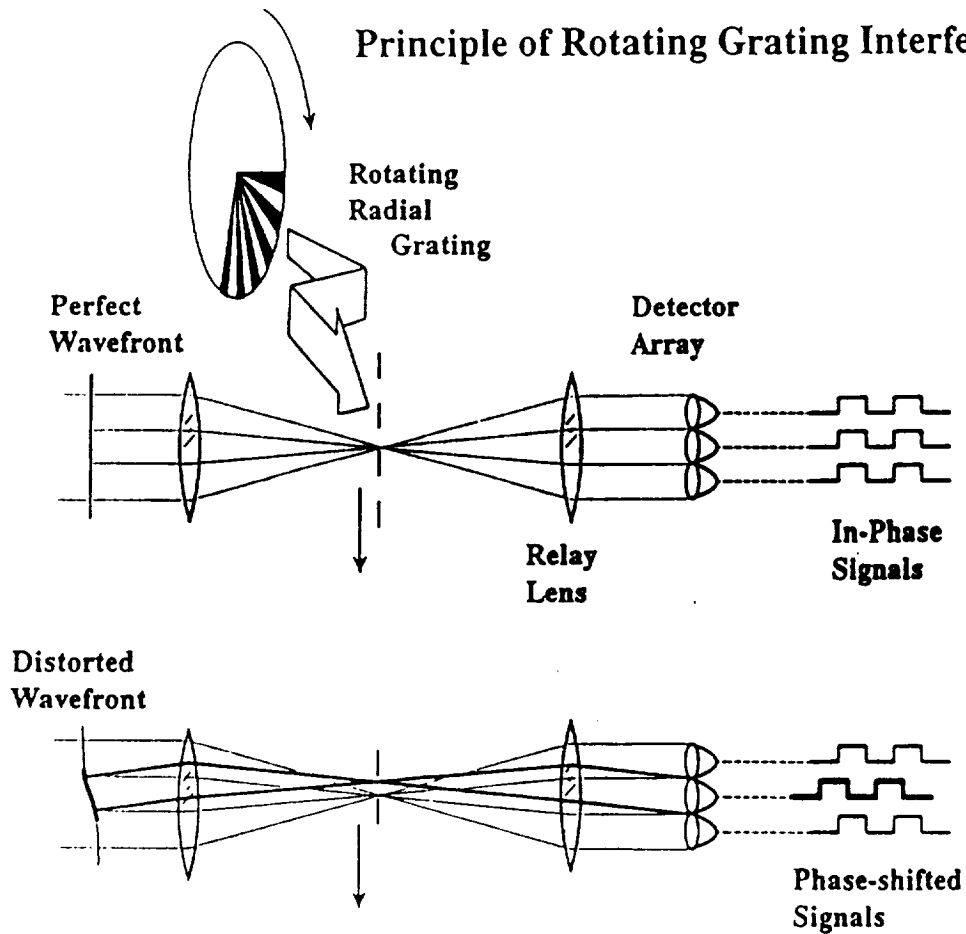
WAVEFRONT CORRECTION VIA "COMMAND RECONSTRUCTOR"

- OBJECTIVE: REMOVE ABERRATIONS FROM OPTICAL WAVEFRONTS

- IMPLEMENTATION:

$$\begin{bmatrix} 120 \times 69 \\ \text{RECONSTRUCTION} \\ \text{MATRIX} \end{bmatrix} \begin{Bmatrix} 120 \text{ MEASURED} \\ \text{GRADIENTS FROM} \\ \text{WFS} \end{Bmatrix} = \begin{Bmatrix} 69 \text{ CORRECTIVE} \\ \text{COMMANDS} \\ \text{TO DM} \\ \text{ACTUATORS} \end{Bmatrix}$$

$$R_C \qquad X \qquad S \qquad = \qquad C$$

- PROBLEM: WHAT IS THE BEST WAY TO FORMULATE R_C, GIVEN:

  - ACTUATOR GAIN AND INFLUENCE FUNCTIONS

  - USE OF SLAVE ACTUATORS AT EDGE OF DM

  - WFS SUBARPERTURE/DM ACTUATOR GEOMETRY

  - OBSCURATIONS IN OPTICAL PATH

  - ANGLE OF INCIDENCE = 10° AT DM

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"COMMAND RECONSTRUCTOR"

- OBTAINED DIRECTLY FROM IN-SITU CALIBRATION

- MEASURE WFS RESPONSE TO FIXED VOLTAGE COMMAND TO EACH ACTUATOR

$$\begin{bmatrix} 69 \times 120 \\ \text{WFS "MEASUREMENT} \\ \text{MATRIX"} \end{bmatrix} \begin{Bmatrix} 69 \text{ COMMAND} \\ \text{VOLTAGES AT} \\ \text{DM} \end{Bmatrix} = \begin{Bmatrix} 120 \text{ MEASURED} \\ \text{WFS GRADIENTS} \end{Bmatrix}$$

$$M \qquad X \qquad C \qquad = \qquad S$$

INVERSION YIELDS

- LEAST-SQUARES-FIT OF MEASURED GRADIENTS TO OBTAIN
  DESIRED COMMANDS (VOLTAGES) FOR DM

$$C = R_C S, \quad \text{WHERE} \quad R_C = [M^T M]^{-1} M^T$$

- ZERO-PISTON CONDITIONS ADDED PRIOR TO INVERSION

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E-7

MEASURED PSF (CAMERA BLUR REMOVED)
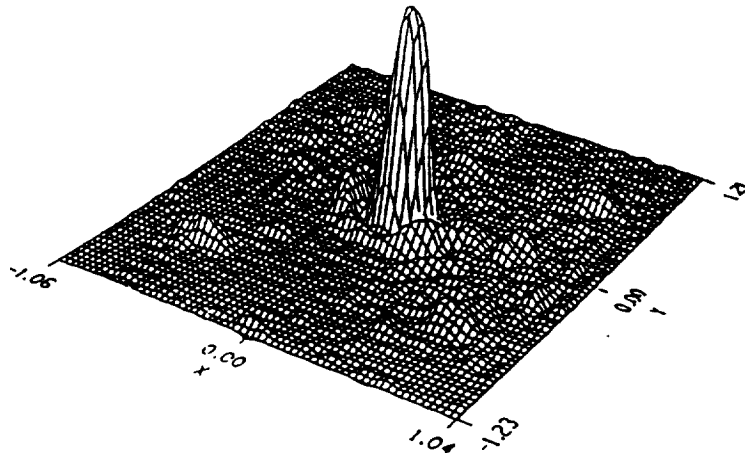
MEASURED PSF

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PERFORMANCE ESTIMATION FROM
IMAGING SYSTEM DATA - PHASE RETRIEVAL

- **PHASE RETRIEVAL**

  - **USE GETRSCHBERG-SAXTON ITERATIVE ALGORITHM TO OBTAIN OPTICAL PHASE ERRORS CONSISTENT WITH IMAGE OF PSF (POINT SPREAD FUNCTION)**

    - **UTILIZE KNOWN OBSCURATION PATTERN AS A CONTSTRAINT IN PUPIL SPACE**

    - **UTILIZE CAMERA DATA AS A CONSTRAINT IN IMAGE SPACE**

- **OPTICAL TRANSFER FUNCTION ANALYSIS**

  - **DETERMINE OTF FROM PSF TO DETERMINE STREHL INTENSITY AND THEREBY OBATIN AN ESTIMATE OF RESIDUAL WAVEFRONT ERRORS**

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E-8

PHASE RETRIEVAL ITERATIVE ALGORITHM

B_0 (PUPIL FUNCTION) ASSUMED KNOWN

A_0 (PSF) MEASURED

INITIAL GUESS

$B_0\ e^{i\phi}$

$B_0\ e^{i\phi'}$

FOURIER TRANSFORMATION

$A'\ e^{i\eta'}$

IS

$|A' - A_0| < \epsilon$

YES

ϕ' IS INPUT PHASE ERROR ESTIMATE

REPLACE B' WITH KNOWN B_0

REPLACE A' WITH DATA, A_0

NO

$B'\ e^{i\phi'}$

INVERSE FOURIER TRANSFORMATION

$A_0\ e^{i\eta'}$
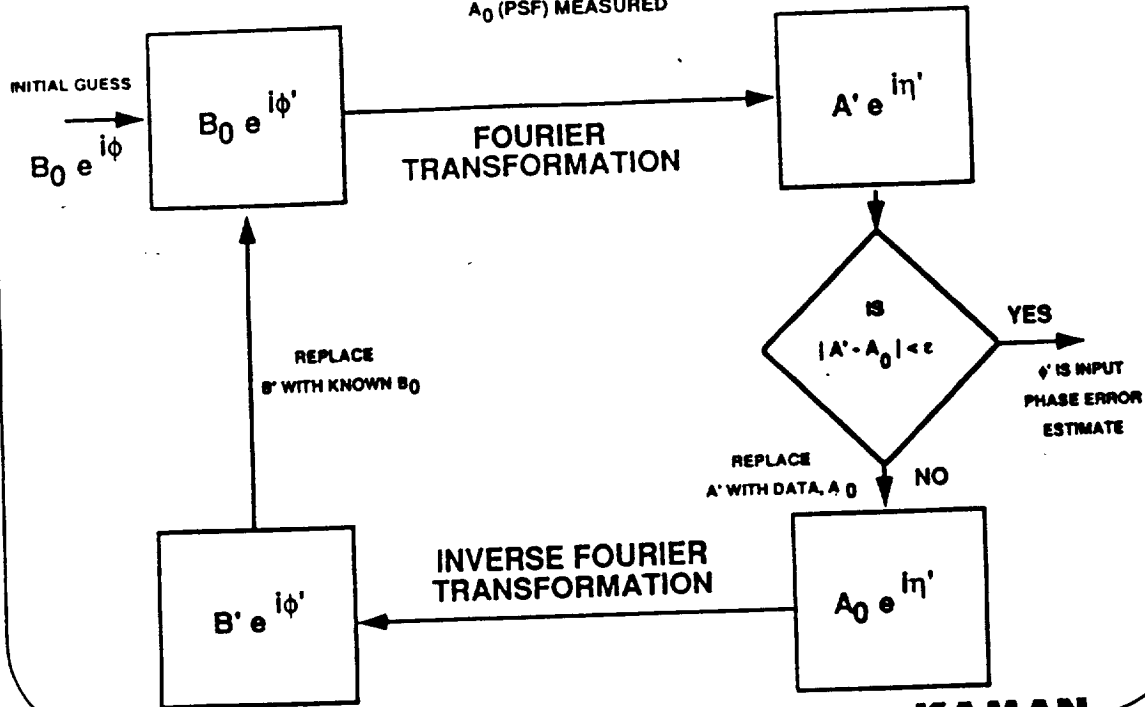
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RETRIEVED OPTICAL PHASE

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E-9

PERFORMANCE ESTIMATION FROM
IMAGING SYSTEM DATA - STREHL INTENSITY

- THE OTF IS THE FOURIER TRANSFORM OF THE PSF: $OTF(\vec{k}) = \frac{1}{2\pi} \int PSF(\vec{r}) e^{i\vec{k}\cdot\vec{r}} d^2r$

- STREHL INTENSITY IS THE RATIO OF MEASURED ON-AXIS (r = 0) INTENSITY TO THE IDEAL VALUE:

$$\eta_S = \frac{PSF(0)}{PSF_{Ideal}(0)}$$

- ANY SYSTEM ABERRATIONS WILL CAUSE $\eta_S < 1$

  - STANDARD DEVIATION OF SYSTEM ABERRATIONS MAY BE ESTIMATED FROM STREHL RATIO (σ IS IN UNITS OF OPD; λ IS WAVELENGTH AT WHICH PSF WAS MEASURED) :

$$\eta_S = e^{-(2\pi\sigma_{OPD}/\lambda)^2}$$

- ON-AXIS INTENSITY IS THE INTEGRAL OF THE OTF: $PSF(\vec{r}=0) = \int OTF(\vec{k}) d^2k$

- STREHL RATIO CAN BE DETERMINED FROM DATA: $\eta_S = \dfrac{\int OTF(\vec{k}) d^2k}{\int OTF_{Ideal}(\vec{k}) d^2k}$

- SINCE *ALL* SPATIAL FREQUENCIES OF ABERRATIONS ARE INCLUDED, THIS ESTIMATE IS A LOWER BOUND ON WCE PERFORMANCE

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OTF Analysis of PSF
Comparison of Ideal (Theory) and Measurement
PSF Taken With RWG ($\lambda = 0.674$ μm)
DM Finger Mirror and ADA Obscurations

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E-10
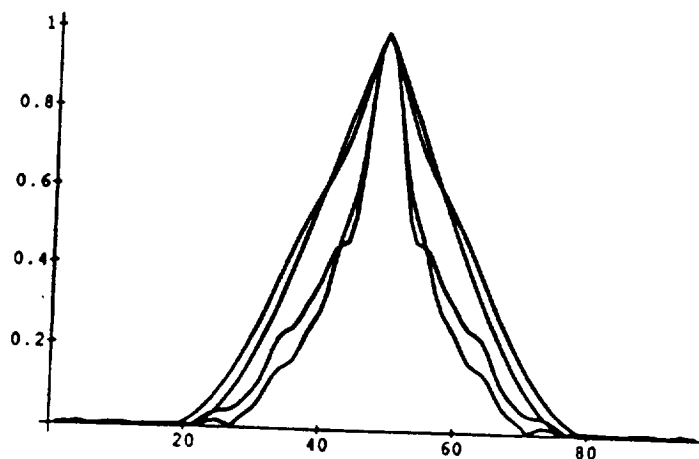
Maximum Allowable RMS Input Wavefront Error
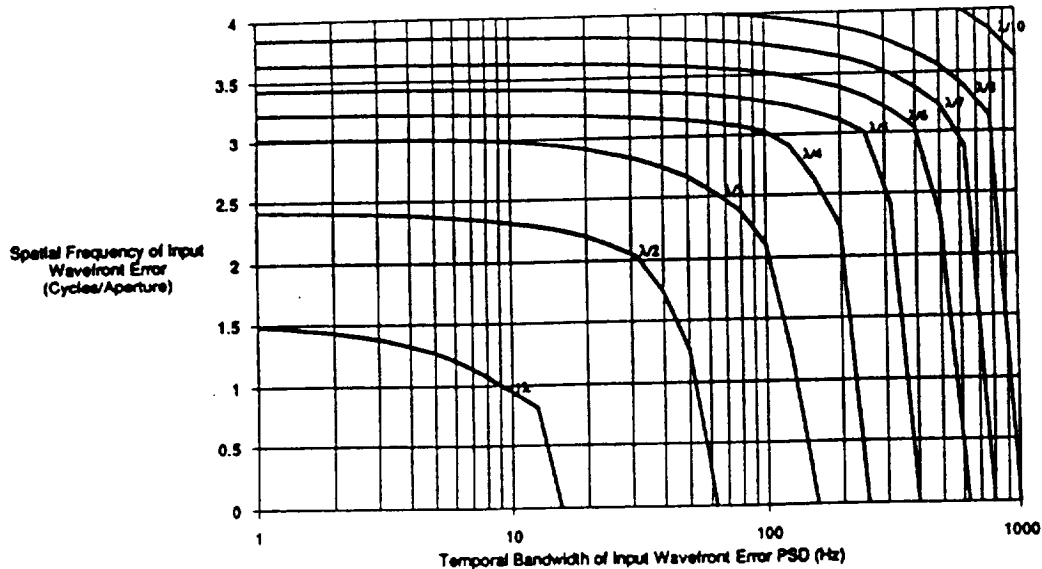
Spatial Frequency of Input Wavefront Error (Cycles/Aperture) vs *Temporal Bandwidth of Input Wavefront Error PSD (Hz)*

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DEFORMABLE MEMBRANE CONTROL SYSTEMS

ISSUES AFFECTING SCALING TO LARGE APERTURES

- ADAPTIVE OPTICS TECHNOLOGY UTILIZING CONTINUOUS FACESHEET DEFORMABLE MEBRANE MIRRORS (DM) NOT SCALABLE TO LARGE APERTURES REQUIRING MANY SUBAPERTURES

  - DMs ARE SMALL-APERTURE DEVICES

  - LARGE APERTURE COLLIMATOR/TELESCOPE SYSTEM REQUIRES ADAPTIVE CONTROL IN A REDUCED BEAM

  - DM ACTUATOR DENSITY REQUIREMENTS GO BEYOND TECHNOLOGY CAPABILITY ($\approx$ 7 mm SPACING)

  - 10 m APERTURE WITH 5 cm SUBAPERTURES WOULD REQUIRE A $\approx$ 1.4 m DM with $\approx$ 30000 ACTUATORS

  - NOT FAULT-TOLERANT - MULTIPLE-ACTUATOR FAILURES CANNOT BE REPAIRED

  - OPTICAL SYSTEM REQUIRES A RELAY PUPIL - COMPLEX OPTICAL SYSTEM DESIGN

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DEFORMABLE MEMBRANE CONTROL SYSTEMS

ISSUES AFFECTING SCALING TO LARGE APERTURES

- SENSED AND CONTROLLED SPACES ARE DIFFERENT

  - DM CONTROLS PISTON OR PHASE -> Φ

  - WAVEFRONT SENSOR SENSES PHASE GRADIENTS -> $\vec{\nabla}\Phi$

  - RECONSTRUCTION OF THE WAVEFRONT FROM THE MEASUREMENTS IS ANALOGOUS TO SOLVING LAPLACE'S EQUATION WITH NEUMANN BOUNDARY CONDITIONS NUMERICALLY

  - REQUIRES A MATRIX OPERATION CONNECTING THE SENSED AND CONTROLLED SPACES

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Surface Control Techniques for Large Segmented Mirrors

Anthony D. Gleckler
Bobby L. Ulich
Chris Sheppard

Kaman Aerospace Corporation
Tucson, Arizona

and

Edward K. Conklin

Forth, Inc.
Manhattan Beach, California

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PAMELA

Phased Array Mirror, Extendible Large Aperture

- Large aperture mirrors composed of small hexagonal segments (subapertures).

- Each segment has three actuators for motion in piston and two tilts.

- Each segment has edge mismatch sensors which measure the relative piston error with respect to its neighboring segments.

- Piston information comes from the edge sensors.

- Tilt information for each subaperture comes from one of two sources depending on the application:

  A wavefront gradient sensor for atmospheric compensation (Adaptive optics).

  A local figure sensor to maintain the optical surface to a desired shape (Active optics).

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PAMELA CONTROL SYSTEM APPROACH

- **MEASURE TILT AND CONTROL TILT**
  - **DOES NOT REQUIRE MASSIVE MATRIX OPERATIONS**
  - **WAVEFRONT SENSOR TECHNOLOGY (HARTMANN) IS MATURE**
    - **SUPPORTS WHITE LIGHT OPERATION**
    - **SUPPORTS PULSED BEAM OPERATION**
    - **MOST PHOTON EFFICIENT**

- **EXTENSIBLE TO LARGE APERTURES (> 10 m)**

PAMELA

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E-13

Control Loop Interaction
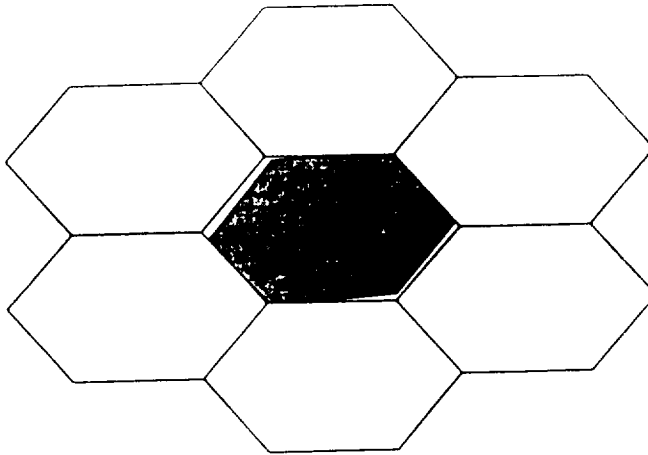
Segment tilt motion affects the piston control loop

Piston motion does not affect the tilt control loop

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SEGMENT CONTROL BLOCK DIAGRAM

Beam incident
on one element

One optical
measurement
per segment

Tilt Sensing
Wavefront
Monitor
(single channel)

$\overline{\Delta\Phi}$ $\Delta\theta_1$ $\Delta\theta_2$

Edge sensor signals
control average phase

Segment
Actuator
Electronics

ΔP_1
ΔP_2
ΔP_3

Signal
Conditioning
Electronics

Subsystem contained
on each segment

PAMELA

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E-14
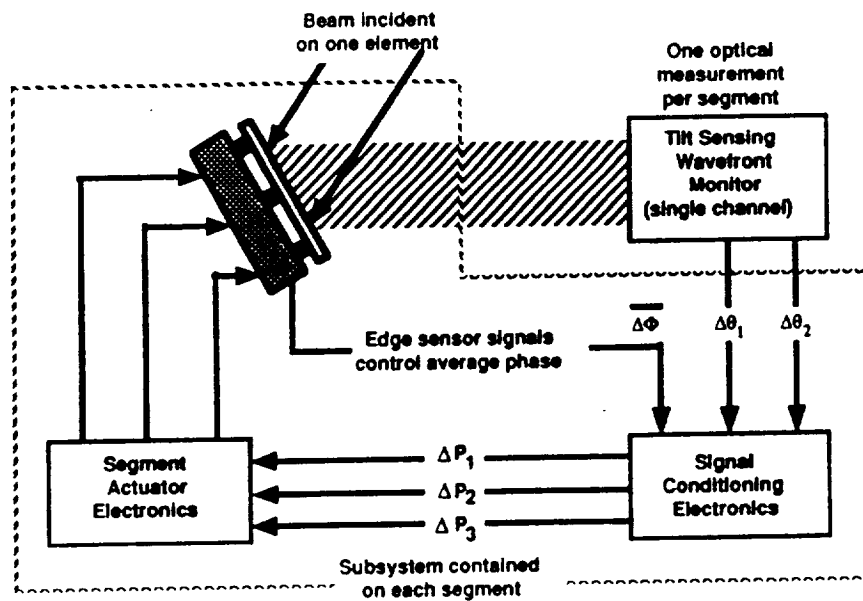
Basic Control Methodology

- Two separate control loops operate for tilt and piston correction.

- The tilt correction operates first.

- The piston correction is then performed at a much higher bandwidth so that the segments form a quasi-continuous surface.

- The overall bandwidth of the system is set by the tilt correction bandwidth.

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NESTED CONTROL ARCHITECTURE

	(Segment Motion)	Actuator (X3)
Wavefront Sensor		
Outer Loop	Edge Sensors (X3)	Inner Loop	Actuator Drive Amplifier (X3)
Wavefront Compensation Circuits (Optional)	Tip-Tilt to Piston Conversion	Segment Control Circuit

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PAMELA

E-15
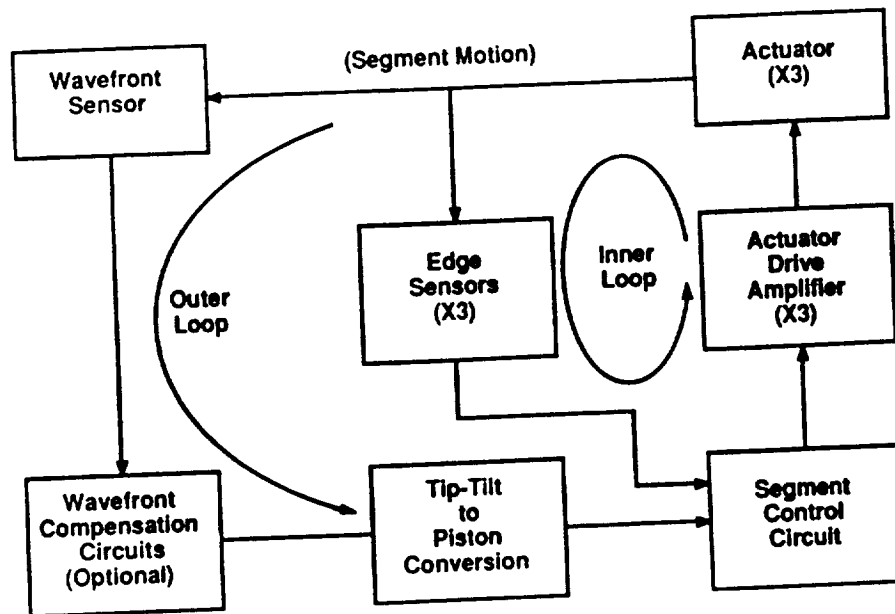
Piston Correction Control Techniques

• **Global Control** - All information comes and goes from one central processor.

• **Local (or Iterative) Control** - The entire mirror surface becomes a large parallel processor. No wavefront reconstructor.

• **Hierarchical Control** - The segments are clustered into "super-segments."

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Global Control

• Large matrix operations are used to reconstruct the wavefront.

• Not scalable to large apertures.

• Example: 15 meter primary mirror with 10 cm segments

    - 20,000 total segments
    - Three degrees of freedom per segment
    - 60,000 x 60,000 reconstructor matrix

Each setting of the surface would take approximately 3×10^9 MAC

At 30 Hz the system would need to make $\sim 10^{11}$ MAC / second

The fastest super-computers (to the authors' knowledge) are on the order of 5×10^9 MAC / second

• Conclusion - Global control is not appropriate for high bandwidth and large numbers of segments.

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Local, or Iterative, Control

- Each segment moves in piston in response to the edge mismatched with its neighbors.

- Convergence of the surface has been shown to be equivalent to solving Poisson's equation in two dimensions.

- Our first piston iteration methods were based on known solutions to Poisson's equation:

  Jacobi (or Least-squares)
  Successive over-relaxation

- A non-Poisson solution, named the "Inner" algorithm, has shown great promise.

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Algorithm Convergence Performance

Global   Inner   Successive Over-Relaxation   Jacobi

Total Number of Segments

300
100
30
10

3   10   30   100   300

Number of iterations to converge

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E-17
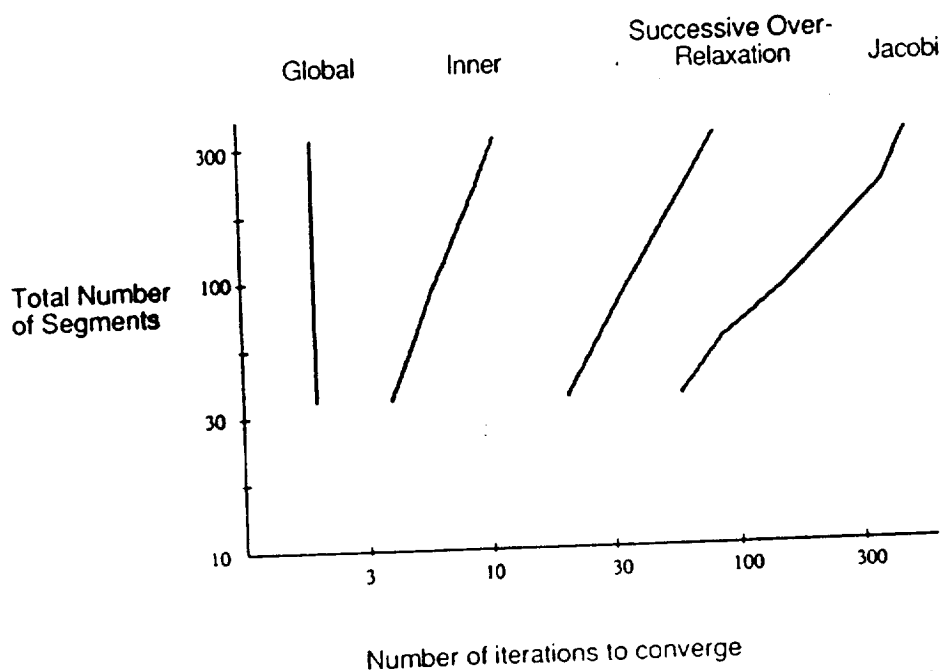
1-Dimensional Wavefront Matching

Input Wavefront

Tilt Correction

After One Piston
Correction Iteration

After Three Piston
Correction Iterations

After Five Piston
Correction Iterations
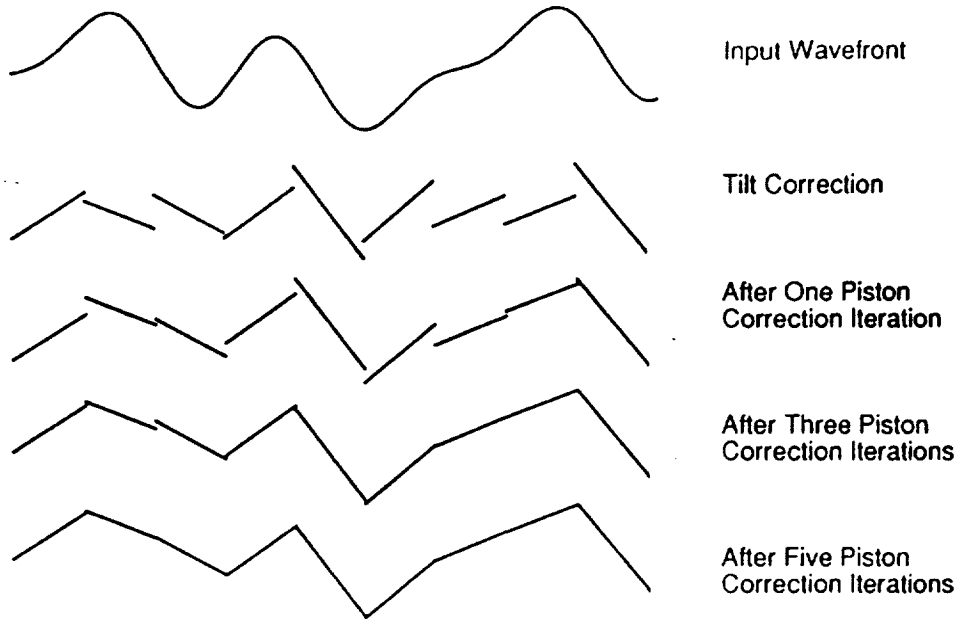
KAMAN
AEROSPACE CORPORATION

Algorithm performance for an annular aperture
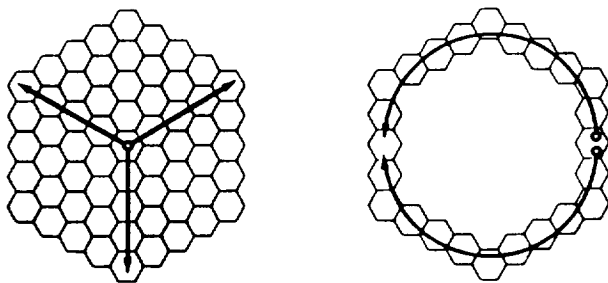
Information paths lengthen with annular aperture.

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AEROSPACE CORPORATION

E-18

Convergence speed versus number of edge sensors

Total Number
of Segments   6 sensors   3 sensors

Number of iterations to converge
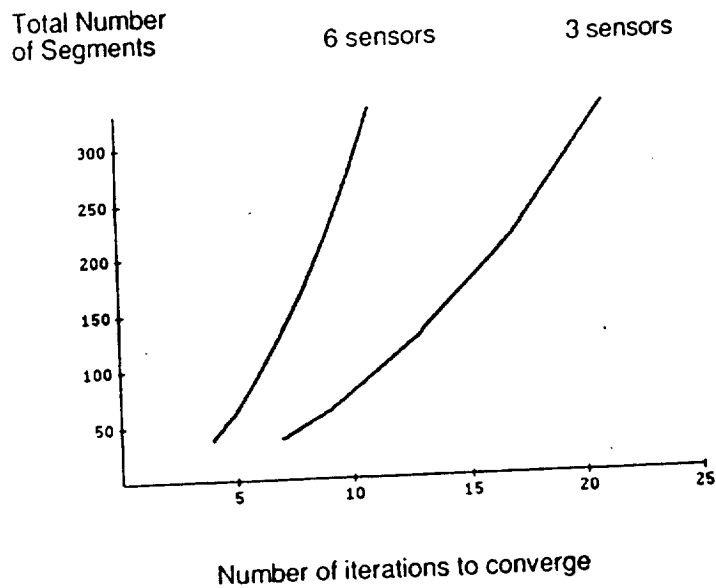
KAMAN
AEROSPACE CORPORATION

Hierarchical Control

- Segments are clustered into super-segments.

- Super-segments can be treated as ordinary segments in terms of control.

- Extremely fast convergence times are possible

- Example: 37 segments per super-segment and 37 super-segments

    - Inner algorithm can converge 37 segments in four iterations.
    - The 37 super-segments can also converge in four iterations.
    - No tilting of the super-segments is necessary.
    - Maximum of eight iterations for convergence of over 1300 segments.

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CONTROL ALGORITHM CHARACTERISTICS

Technique	"Connectivity"	Convergence Behavior
Global (Matrix)	Maximal	Fast
Nearest Neighbor	Minimal	Slow
Hybrid (Hierarchical)	Minimal -> Maximal	Slow -> Fast

- Optimal approach determined by requirements and constraints
- Neural net technology promises to provide an architecture for control
  - "Learn" optimal control from example
  - Vary "connectivity" via weights

KAMAN

E-20

GROUND-TO-SPACE HIGH POWER LASER PROPAGATION

D. P. GREENWOOD

MIT LINCOLN LABORATORY

PRESENTED AT THE TECHNOLOGY WORKSHOP ON LASER BEAMED POWER:
FROM EARTH TO THE MOON AND OTHER APPLICATIONS

NASA-Lewis

5 FEBRUARY 1991

GROUND-BASED SHORT-WAVELENGTH LASER RELAY MIRROR APPROACH
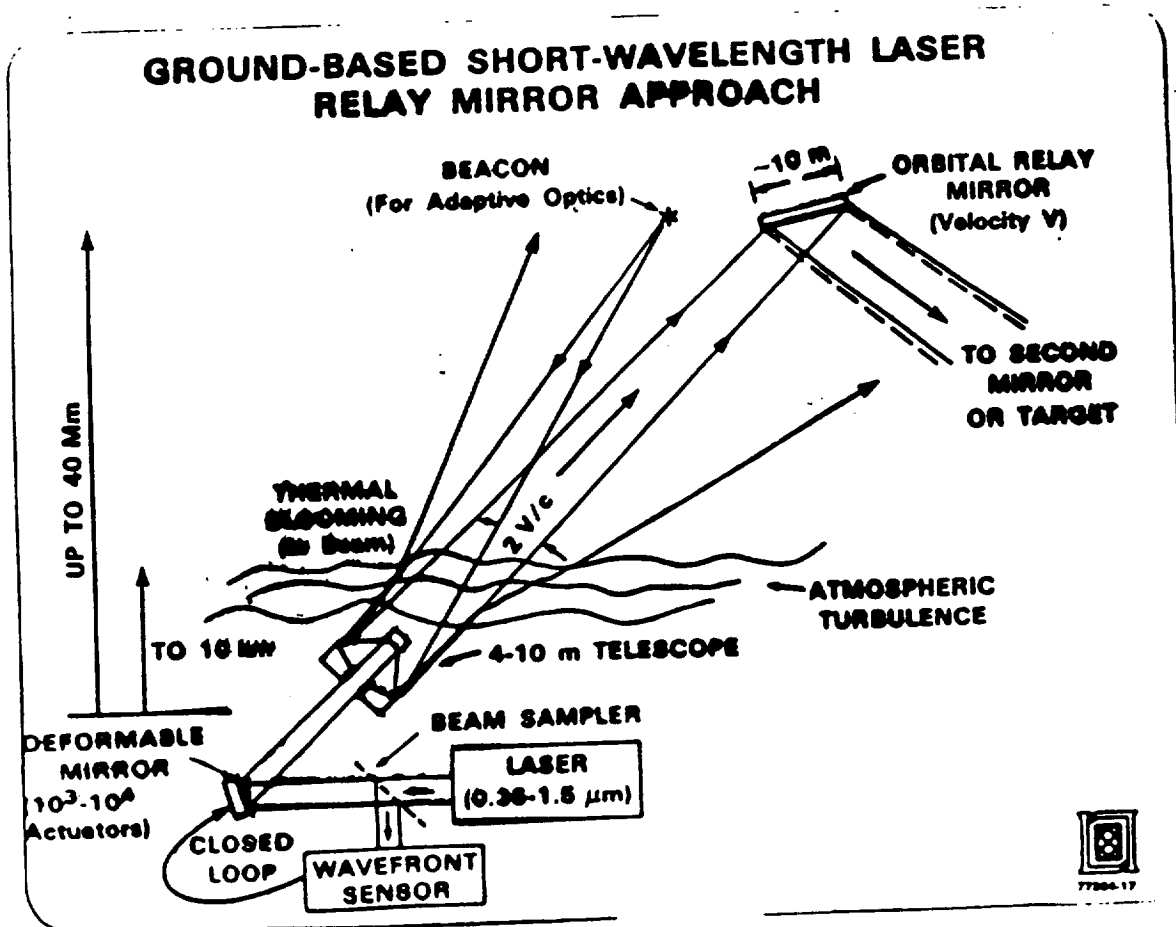
ATMOSPHERIC LIMITATIONS TO PROPAGATING
HIGH-POWER LASER BEAMS

- **EXTINCTION (scattering and absorption)**

- **TURBULENCE (random temperature variations)**

- **THERMAL BLOOMING (interaction between beam and medium)**

ATMOSPHERIC TRANSMISSION vs. WAVELENGTH
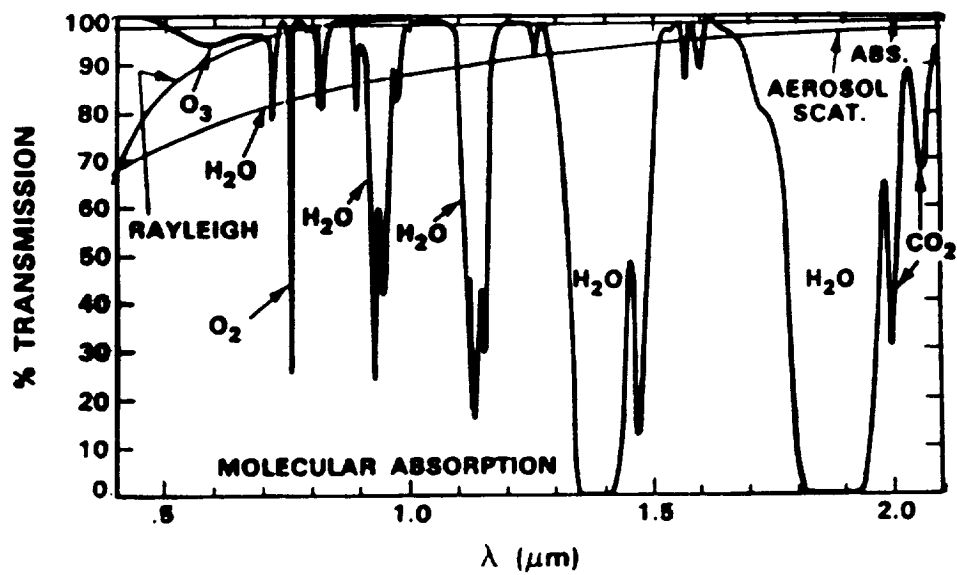
ATMOSPHERIC EFFECTS
IN LASER-BEAM PROPAGATION TO 40 Mm

TURBULENCE

3.5 m/1 μm

400 m

THERMAL BLOOMING

1 MW/1 m/1 μm

1.2 km
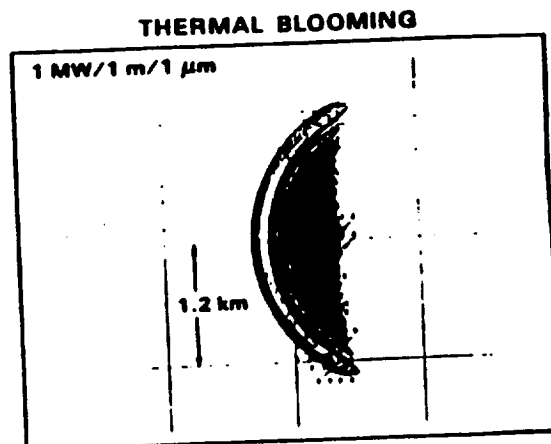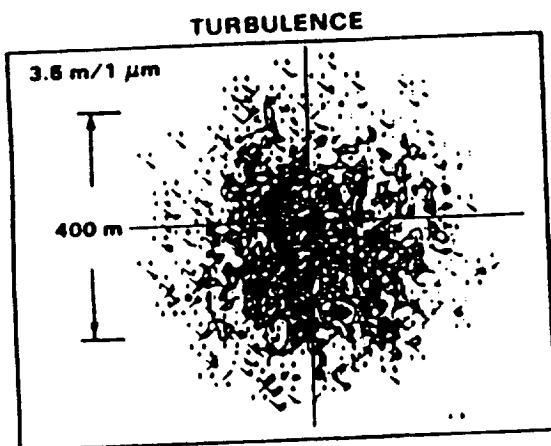
THERMAL BLOOMING

- THERMAL BLOOMING IS THE SPREADING OF A LASER BEAM THAT RESULTS FROM ABSORPTION IN THE ATMOSPHERE OF SOME OF THE LASER ENERGY

- THE HEATED ATMOSPHERE BEHAVES LIKE A POWER-DEPENDENT DIVERGENT LENS

- EVEN WEAK ABSORPTION (Few %) CAN CAUSE SEVERE SPREADING FOR LASER POWERS OF CURRENT INTEREST

THERMAL BLOOMING WILL LIMIT HIGH-ENERGY LASER PROPAGATION
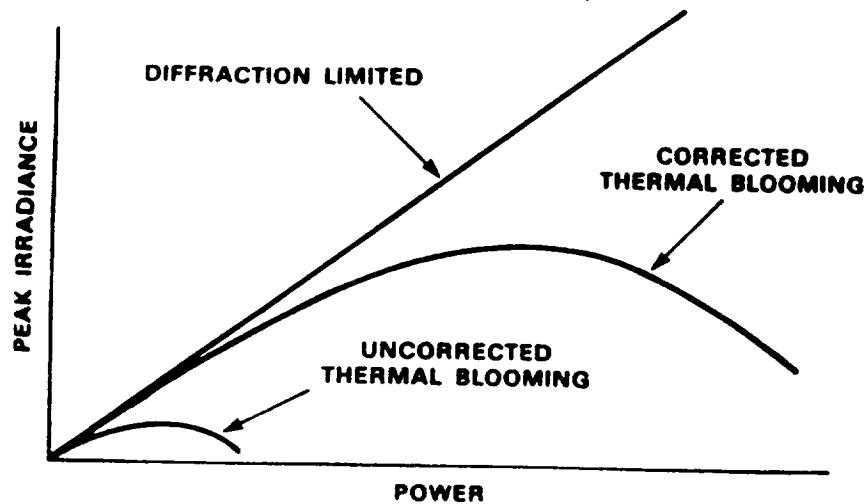
- WHAT IS THE LIMIT?
- HOW CAN IT BE EXTENDED?

ATMOSPHERIC-COMPENSATION PROGRAM AT LINCOLN LABORATORY

- OBJECTIVES:

  - TO ASSESS THE EFFECTS OF THE ATMOSPHERE ON OPTICAL WAVE PROPAGATION, AND

  - TO DEVELOP THE MEANS TO COMPENSATE FOR ATMOSPHERIC ABERRATIONS USING ADAPTIVE OPTICS AND RELATED TECHNIQUES

- APPROACH:

  - DEVELOP EXPERIMENTAL SYSTEMS TO MEASURE AND CORRECT FOR ATMOSPHERIC TURBULENCE AND RELATED ABERRATIONS

  - DEVELOP ANALYTICAL TOOLS TO SUPPORT EXPERIMENTS

- PRINCIPAL SPONSORSHIP:

  - DoD: SDIO, ARMY, NAVY, AIR FORCE, DARPA

ATMOSPHERIC-COMPENSATION PROGRAM
("ACE," Completed 1985)

- **OBJECTIVE:**
  - TO INVESTIGATE THE ABILITY OF ADAPTIVE OPTICS TO COMPENSATE ATMOSPHERIC TURBULENCE AT LOW LASER POWERS, USING BEACON SOURCES FOR WAVEFRONT SENSING

- **APPROACH:**
  - DEVELOP A 69-CHANNEL ADAPTIVE-OPTICS SYSTEM
  - INSTALL AT AMOS SITE IN MAUI (60-cm Beam Director)
  - TEST OVER ATMOSPHERIC PATHS TO:

    AIRCRAFT
    SOUNDING ROCKETS
    STARS

- **CONCLUSION (Reached in 1985):**
  - ATMOSPHERIC TURBULENCE CAN BE EFFECTIVELY COMPENSATED, BUT ADDITIONAL WORK IS REQUIRED IN COMPONENTS TECHNOLOGY AND IN THE DEVELOPMENT OF SYNTHETIC BEACON SOURCES

ROCKET TRAJECTORY FOR PHASE III ATMOSPHERIC COMPENSATION TESTS

COMPENSATION OF A VISIBLE LASER FROM GROUND TO SPACE DEMONSTRATED

UNCOMPENSATED   COMPENSATED

RELATIVE POWER

RELATIVE BEAM DIAMETER

REFERENCE: "GUIDE TO THE STRATEGIC DEFENSE
INITIATIVE," R.H. BUENNEKE, ed.

Prepared by

GROUND-BASED LASER FOR ASAT APPLICATION

UNCLASSIFIED

VELOCITY V

POINTING
DIRECTION

SYNTHETIC
BEACON

TRACKING
DIRECTION

UP TO 40 km

TO 90 km

2V/c

ATMOSPHERIC
TURBULENCE
(to 10 km)

4-10 m
TELESCOPE

BEACON
LASER

DEFORMABLE
MIRROR
(10^3 - 10^4
Actuators)

HIGH-ENERGY
LASER
(0.35-4 μm)

WAVEFRONT
SENSOR

TARGET
TRACKER

UNCLASSIFIED

Prepared by

SWAT (Short-Wavelength Adaptive Techniques) PROGRAM

- OBJECTIVES:
  - TO DEVELOP THE TECHNIQUES REQUIRED TO COMPENSATE ATMOSPHERIC TURBULENCE OVER A SPACE-TO-GROUND PATH, WITH THE USE OF NATURAL, MAN-MADE, AND SYNTHETIC BEACONS, AND
  - TO ADVANCE GENERALLY THE TECHNOLOGY OF ADAPTIVE OPTICS

- APPROACH:
  - DEVELOP AN ADAPTIVE-OPTICS SYSTEM AT THE 241-CHANNEL/1-kHz LEVEL
  - DEVELOP LASERS SUITABLE FOR RAYLEIGH AND SODIUM EXPERIMENTS

    DYE LASER AT 508 nm
    SOLID-STATE LASER AT 589 nm TO PUMP STRATOSPHERIC SODIUM AT 90 km

  - INSTALL ON 60-cm TELESCOPE AT AMOS (Air Force Maui Optical Site)
  - CONDUCT EXPERIMENTS USING STARS AND SATELLITES AS DIAGNOSTICS

SWAT OPTICAL BENCH IN MAUI
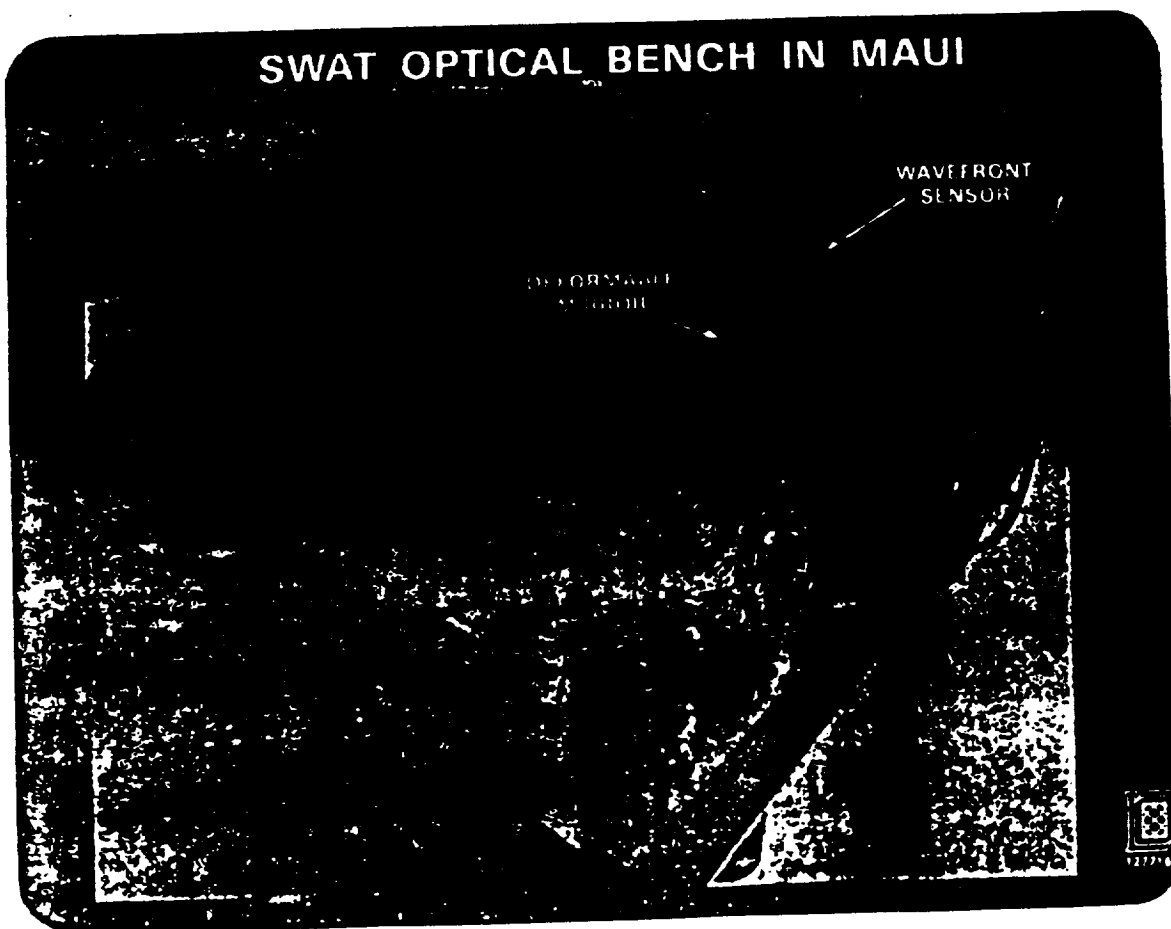
SWAT TESTS TO LACE SATELLITE
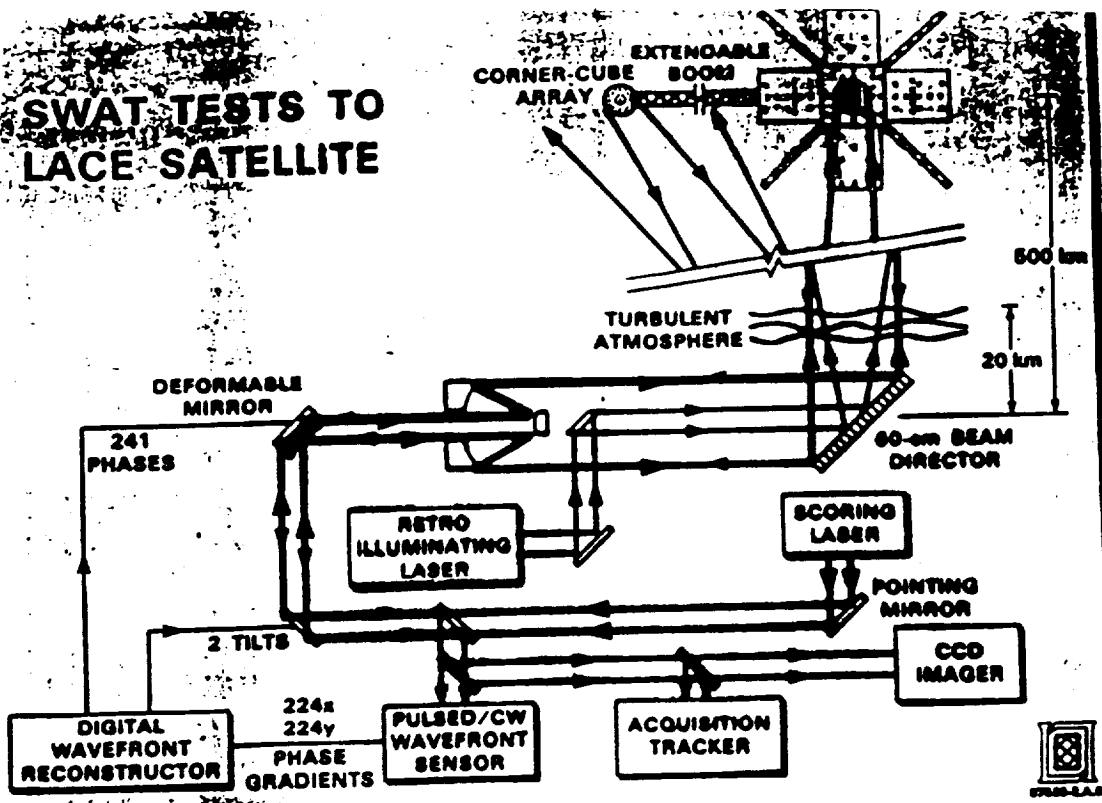
GROUND-TO-SPACE PROPAGATION EXPERIMENTS FROM AMOS SITE IN MAUI

LACE Data   30 November 1990

SMC 182, Samples 180-184
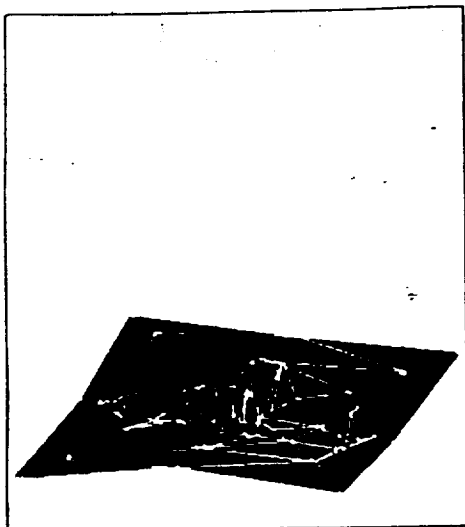
SMC 181, Samples 160-164
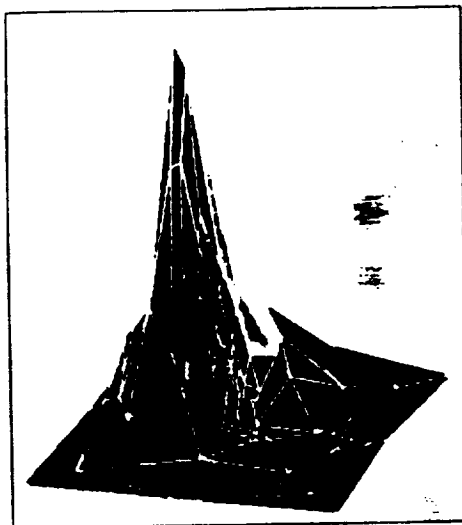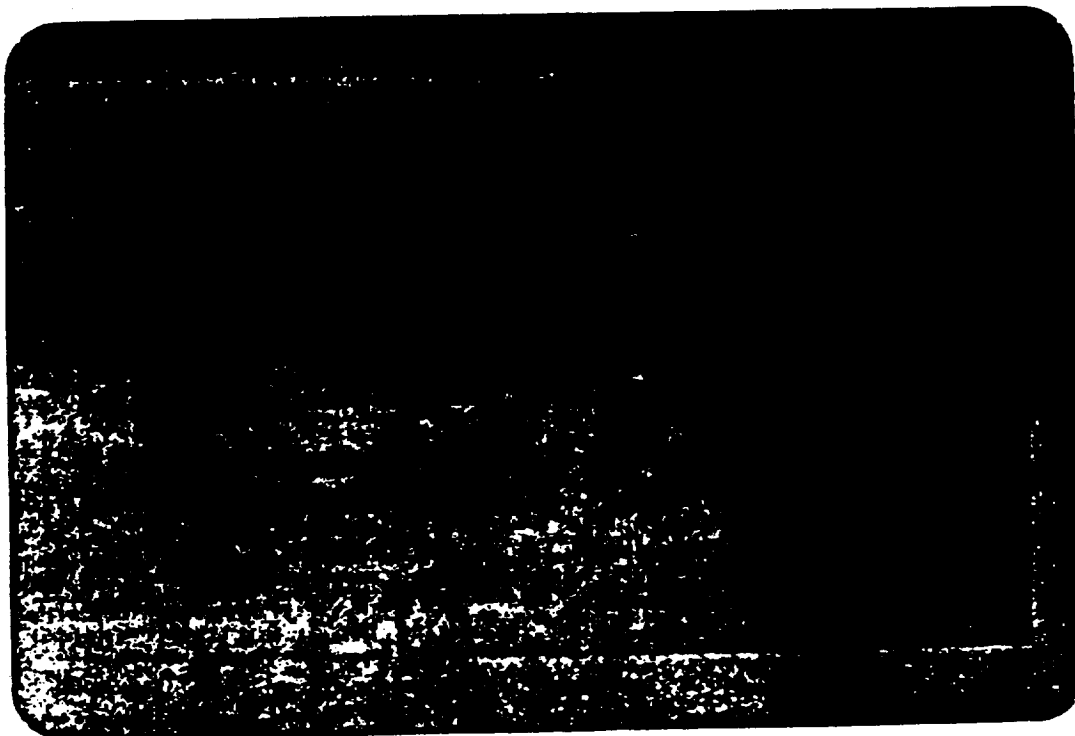
Uncompensated

Compensated

ASTRONOMICAL APPLICATIONS
OF ADAPTIVE OPTICS
WITH SYNTHETIC BEACONS

FIREPOND TELESCOPE

- 60 cm ACQUISITION TELESCOPE
- X-BAND SAFETY RADAR
- 1.2 m LASER RADAR TELESCOPE
- 35 cm, 5 SCHMIDT TELESCOPE
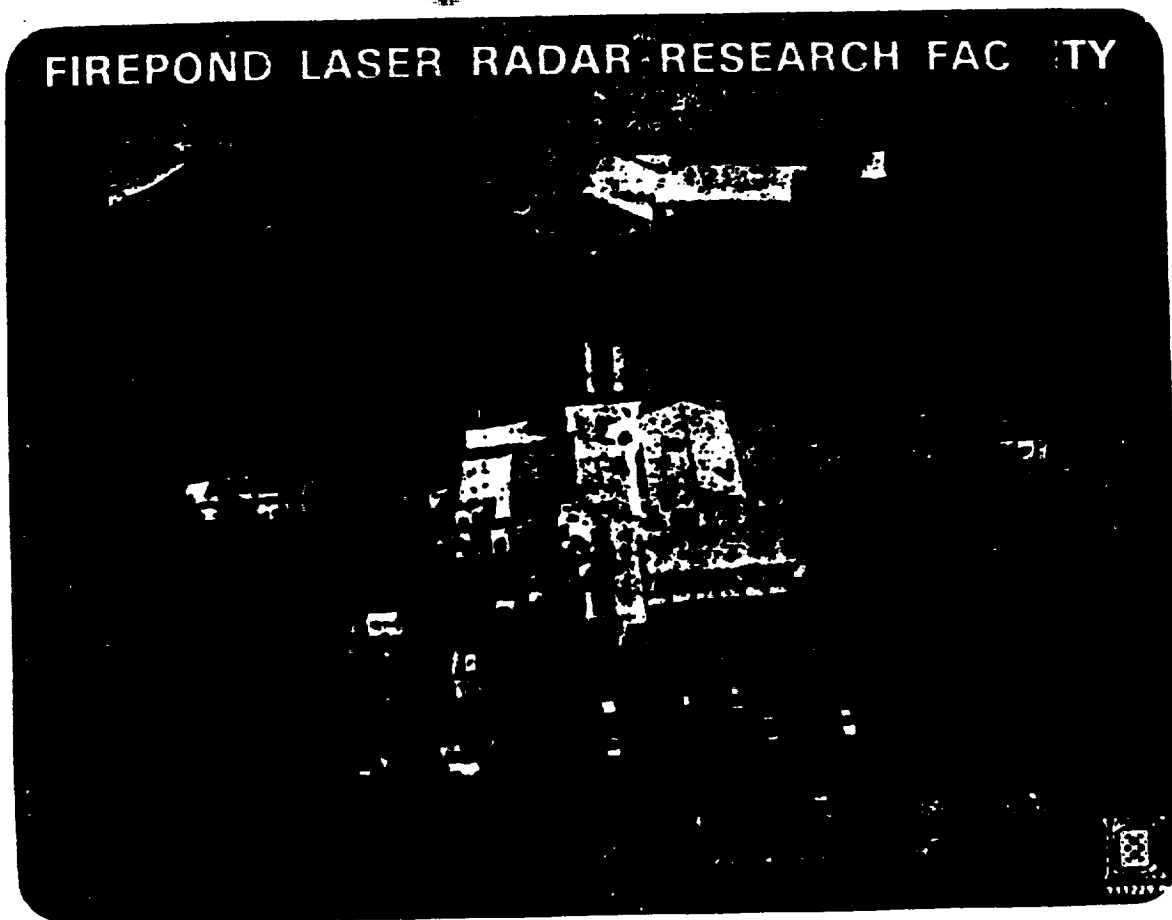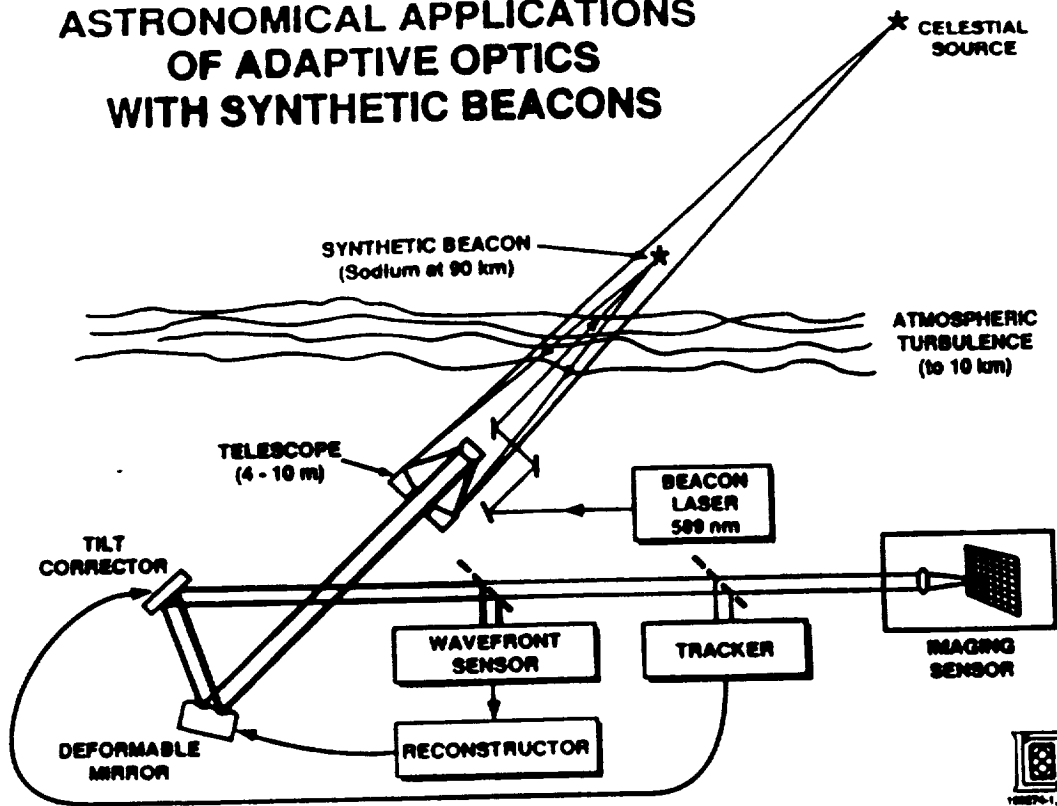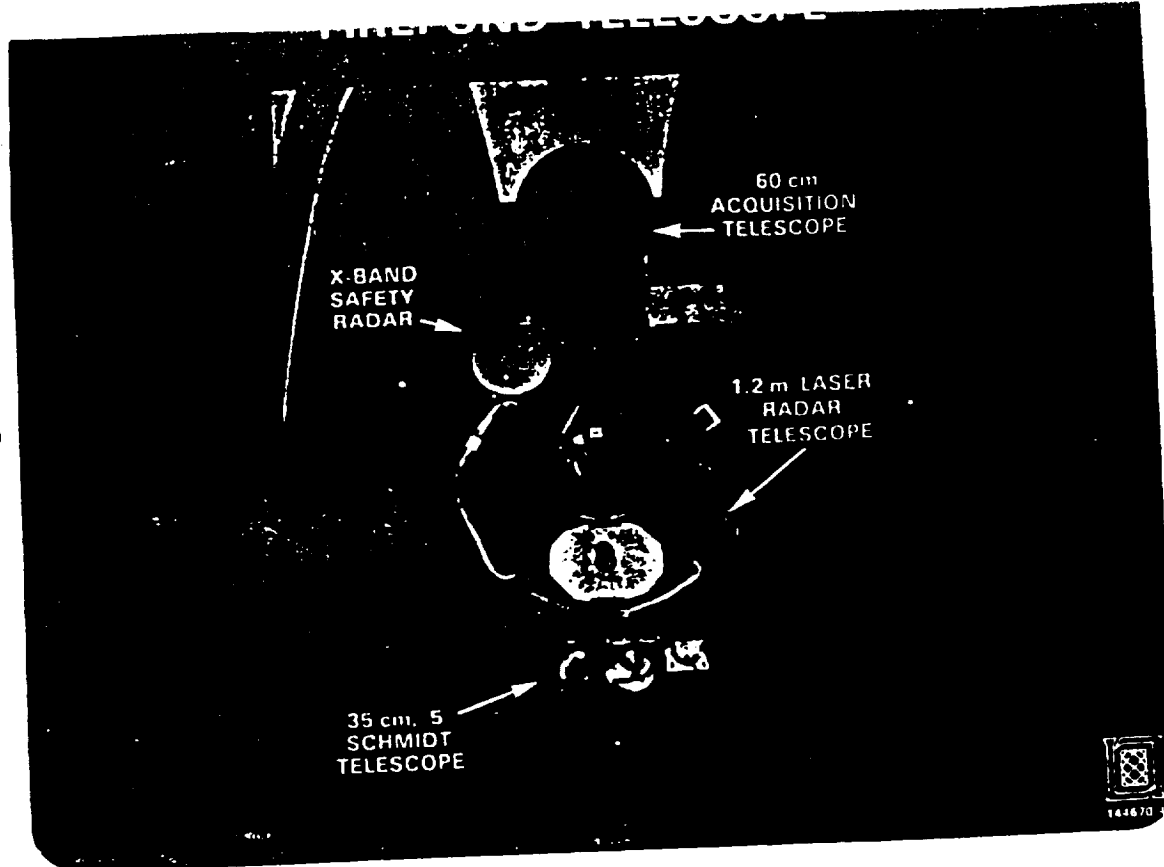
Prepared by

STAR IMAGE COMPENSATION EXPERIMENT
Images of Vega Recorded by SWAT on 25 June 1990

Compensated Image
Strehl = 0.4

Uncompensated Image
Strehl = 0.04

3.8 arc-sec

F-11
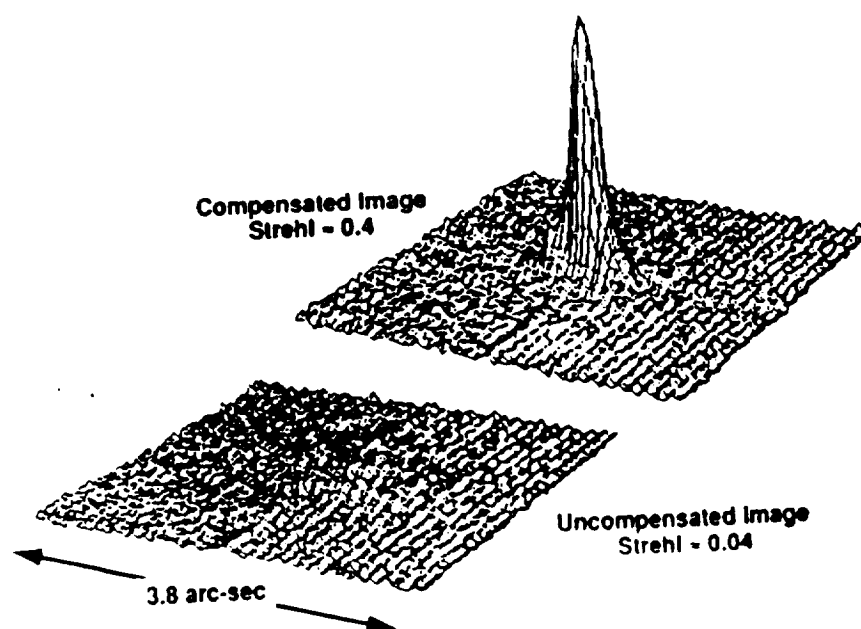
LASER SYSTEM FOR ATMOSPHERIC
OPTICAL DISTORTION COMPENSATION

MOLLY, A TIME-DEPENDENT PROPAGATION CODE: DESIGN HIGHLIGHTS

- **HARDWARE**

  - OPTIMIZED FOR CRAY-2: LARGEST-MEMORY SUPERCOMPUTER (256 Million 64-Bit Words)

- **SPECIAL MODELING CAPABILITIES**

  - REALISTIC AND GENERAL DEFORMABLE-MIRROR FITTING

  - FINITE CORRECTION BANDWIDTH

  - NONZERO CORRECTION DELAY

  - MULTILINE PROPAGATION

  - ATMOSPHERIC THERMAL DIFFUSION

MULTILINE
HEL

DEFORMABLE MIRROR
WITH REALISTIC
INFLUENCE FUNCTION

HARTMANN
(Shown Here)
OR SHEARING
WAVEFRONT
SENSOR

SERVO

IMAGING
OPTICS

REALISTIC (Incl. Orogrande)
ATMOSPHERES: ABSORPTION,
SCATTERING, TURBULENCE,
TWO-DIMENSIONAL WINDS,
KOLMOGOROV RANDOM WIND
FLUCTUATIONS, SLEW

TILT
MIRROR

BEACON

SERVO

FOCAL SPOT
CENTROID DETECTOR
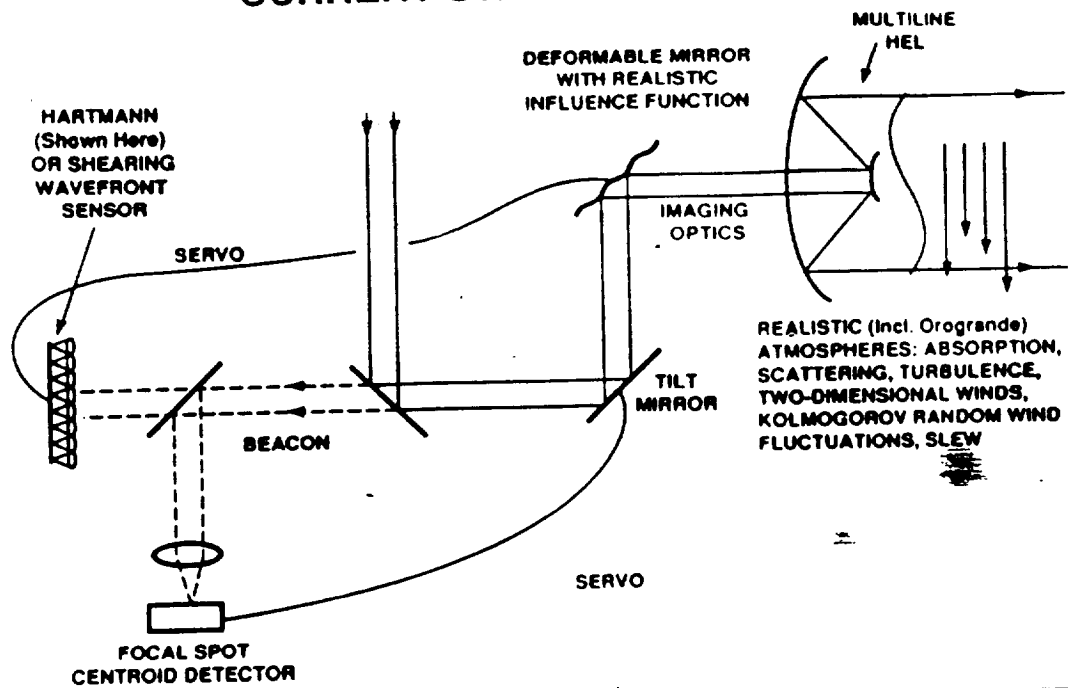
Prepared by

EFFECT OF INSTABILITY ON PHASE-COMPENSATED HIGH-ENE GY LASER BEAM

- D = 3.5 m,   m µm
- ACTUATOR SPACING   cm
- ZERO SLEW

PHASE AT TOP OF ATMOSPHERE

P = 10 MW

P   20 MW

WIND DIRECTION
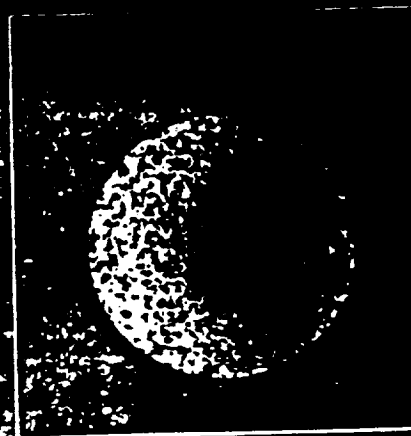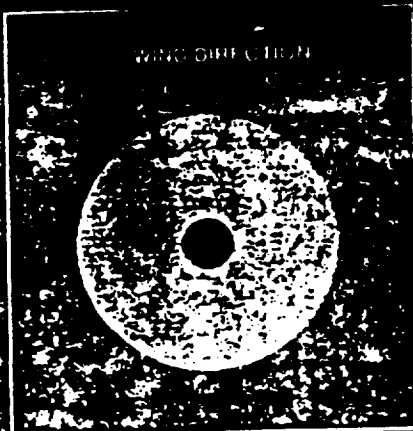
STREHL RATIO ~ 0.8   STREHL RATIO ~ 0.1

Prepared by

BASELINE RESULTS
STREHL RATIOS FOR
VARIOUS POWERS AND DIAMETERS

WITH TWO REALIZATIONS OF KOLMOGOROV FLUCTUATIONS
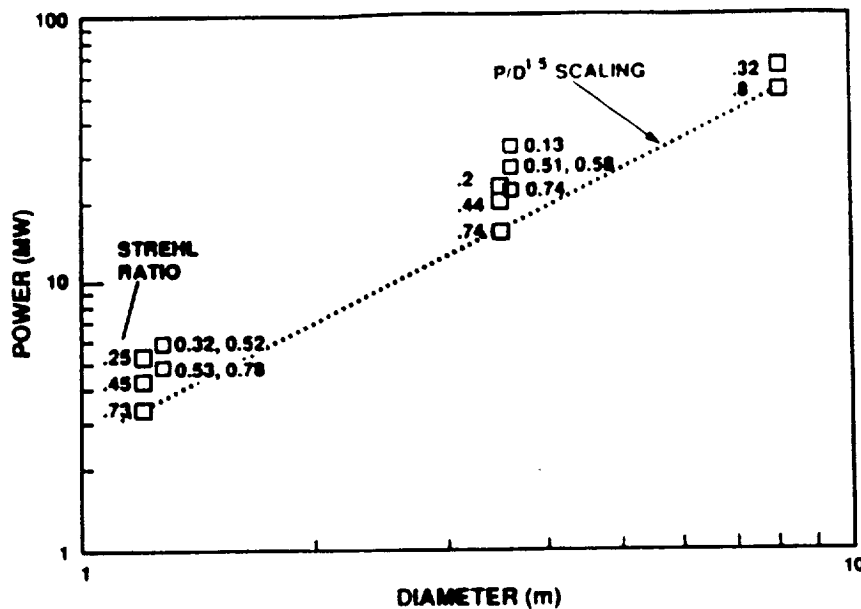
LABORATORY THERMAL-BLOOMING
COMPENSATION EXPERIMENTS

- OBJECTIVES:
    - EXAMINE CORRECTABILITY OF STRONG THERMAL BLOOMING UNDER CONDITIONS EXPECTED TO GENERATE PCI (Phase-Conjugate Instability)
    - COMPARE EXPERIMENTAL RESULTS WITH MOLLY SIMULATIONS TO BENCHMARK CODE PERFORMANCE

F-14

LABORATORY THERMAL BLOOMING EXPERIMENT

OPTICAL BENCH

WAVEFRONT SENSOR

MIRROR DRIVE ELECTRONICS

DEFORMABLE MIRROR

BEAM-CONTROL COMPONENT DEVELOPMENT AT LINCOLN LABORATORY

	1985	1990	FUTURE
COOLED, LOW-COST DEFORMABLE MIRRORS	69-ACTUATOR HICLAS	241-ACTUATOR ITEK & UTOS LCDMs	SCALE TO LARGER STROKES & SIZES, IMPROVE REPAIRABILITY, USE NEC ACTUATOR
WAVEFRONT SENSORS	69-CHANNEL SHEARING (ACE), DISCRETE SENSORS	241-CHANNEL BINARY-OPTIC, CCD HARTMANN (SWAT)	IMPROVE CCDs, STUDY HARTMANN vs. SHEARING
SHARED APERTURE COMPONENTS	NONE (For High Power)	SAOD (SKYLITE), HAC SUBSCALE BLIND GRATING	IMPROVE EFFICIENCY, DURABILITY
RECONSTRUCTORS	RESISTOR NETWORK	DIGITAL MATRIX MULTIPLY	RELAXATION METHOD
COOLED FAST STEERING MIRRORS	16-cm TRAPAF AND HOST	PRELIMINARY 50-cm 300-Hz DESIGN (Completed in 1/88)	DEVELOP LARGE HIGH-BANDWIDTH MIRRORS

FAR-FIELD PEAK IRRADIANCE AS FUNCTION OF DISTORTION NUMBER

- P = 0.5-2.5 WATTS, V = 1.4 cm/s, BANDWIDTH = 200 Hz
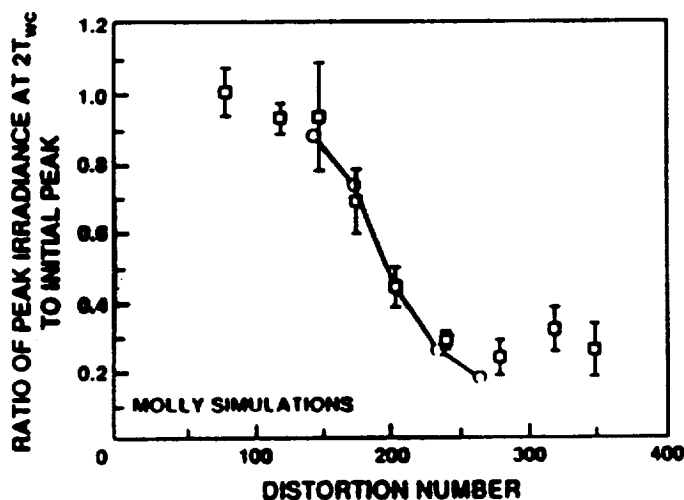
ERROR BARS FROM MULTIPLE EXPERIMENTAL MEASUREMENTS

DEFORMABLE MIRROR AND DRIVERS

- MIRROR BUILT BY ITEK
  - 17 - 17 ARRAY WITH ROUNDED CORNERS
  - 241 ACTUATORS
  - ACTUATOR MOTION ±?
  - ACCURACY < ?/20
- ACTUATOR DRIVERS BUILT BY LINCOLN LABORATORY
  - SETTLING TIME <100 μsec
  - NONLINEAR ACTUATOR CALIBRATION
  - TEMPERATURE COMPENSATION

COOLED DEFORMABLE MIRRORS

	UTOS HICLAS	ITEK LCDM
ACTUATORS	69	241 (+ Two Guard Bands)
STROKE	30 μm	4 μm
ACTIVE AREA	16 cm DIAMETER	16 cm DIAMETER
SURFACE FIGURE	~0.1 λrms(λ = 0.633 μm)	~0.02 λrms(λ = 0.633 μm)

LOW-COST UNCOOLED DEFORMABLE MIRROR

- **LOW-COST ELECTROSTRICTIVE ACTUATORS NOW AVAILABLE FROM NEC**
  - 8-μm STROKE AT 150 V (4-μm, 16-μm Actuators Also Available)
  - ≤ 15 % HYSTERESIS (Similar To Magnetostrictive Actuators)

- **PROTOTYPE 13-ACTUATOR MIRROR UNDER DEVELOPMENT AT LINCOLN LABORATORY IS NEARLY COMPLETE**

- **TECHNIQUE FOR HYSTERESIS REDUCTION IS BEING DEVELOPED**

- **241-ACTUATOR MIRROR WAS PLANNED FOR EARLY FY 92, FOLLOWED BY 2000-ACTUATOR MIRROR**

PULSED WAVEFRONT SENSOR
PRINCIPLE OF OPERATION

ARRAY OF LENSLETS IN ENTRANCE PUPIL

2-D DETECTOR ARRAY IN FOCAL PLANE

TO PROCESSOR AND DIGITAL RECONSTRUCTOR

INCOMING WAVEFRONT
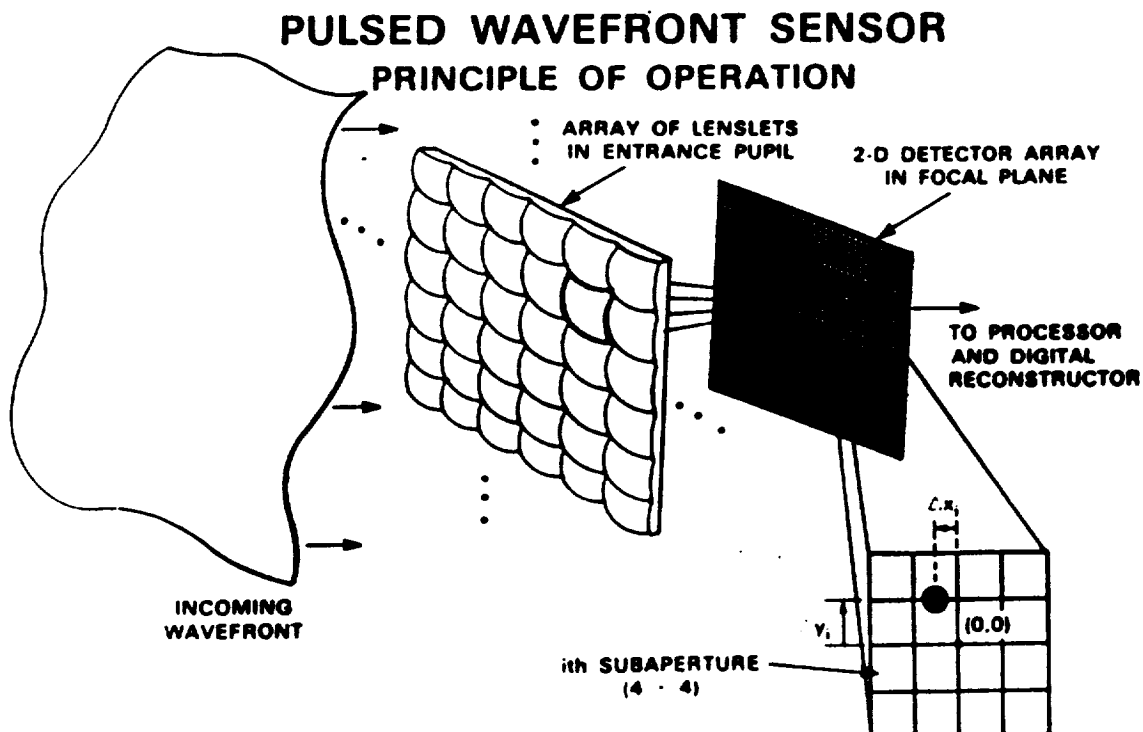
ith SUBAPERTURE (4 · 4)

- **LOCAL PHASE GRADIENTS AT ith SUBAPERTURE ARE PROPORTIONAL TO $(\Delta x_i, \Delta y_i)$**

- **DIGITAL RECONSTRUCTOR COMPUTES PHASE FROM MEASURED GRADIENTS**

CCD CAMERA

Prepared by

LINCOLN LABORATORY
WAVEFRONT SENSOR

- **SENSOR FEATURES**
  - 241-SUBAPERTURE HARTMANN SENSOR
  - MEASURES TO $\lambda/20$ AT 4000 CAMERA PHOTONS/SA/CHANNEL
  - LINCOLN LAB BACK-ILLUMINATED CCD CAMERAS
  - NO IMAGE INTENSIFIERS REQUIRED
  - BINARY-OPTICS LENSLET ARRAYS
  - POCKELS CELL GATING

- **PROCESSOR FEATURES**
  - TABLE-DRIVEN, PIPELINED ARCHITECTURE
  - 6 μs FROM CAMERA DATA IN TO FIRST GRADIENT OUT
  - CAMERA OFFSET AND GAIN CORRECTION, TILT REFERENCE

QUANTUM EFFICIENCY OF CCD IMAGERS
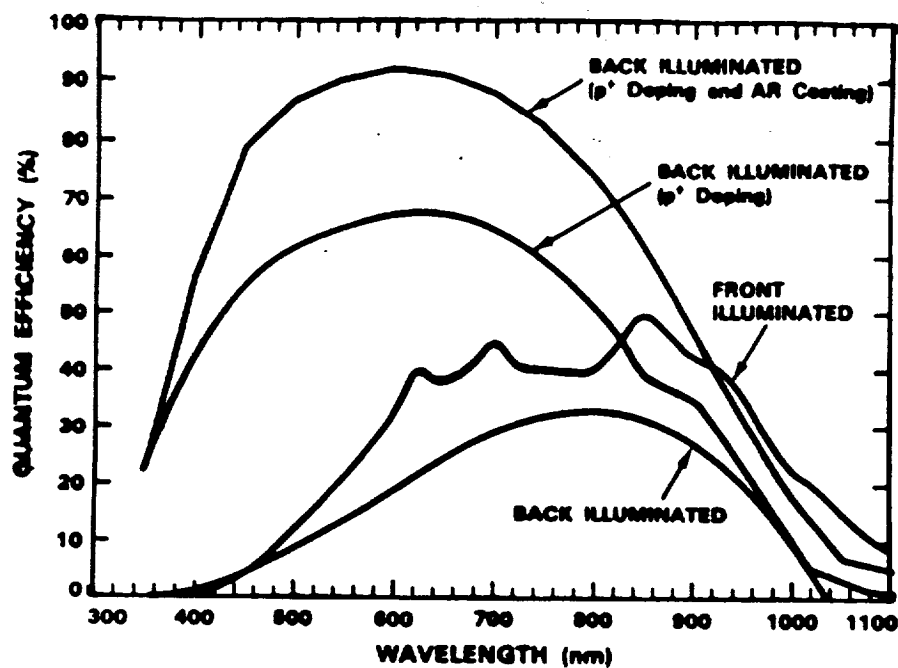
LOW NOISE OUTPUT AMPLIFIER

1 STAGE OUTPUT AMPLIFIER   2 STAGE OUTPUT AMPLIFIER

- UNIQUE TRANSISTOR STRUCTURE YIELDS LOW OUTPUT NOISE
  - BURIED CHANNEL MOSFET YIELDS LOW 1/f NOISE
  - GATE-DRAIN STRUCTURE MINIMIZES MILLER FEEDBACK CAPACITANCE
- CAMERA SYSTEM NOISE: 30 e⁻rms

Prepared by

POLARIZATION SHEARING WAVEFRONT SENSOR

TO OTHER AXIS — SHEAR ELEMENT — 1/4 WAVE PLATE

INPUT

CCD   P1 $\pi/2$

P0   C C D

P3   C C D $3\pi/2$

P2   C C D

π

$$\frac{\partial \varphi}{\partial x} = K \arctan\left(\frac{P_3 - P_1}{P_0 - P_2}\right)$$

PHASE RECONSTRUCTION

⑦ →5→ ⑧ →6→ ⑨

↑10   ↑11   ↑12

④ →3→ ⑤ →4→ ⑥

↑7   ↑8   ↑9

① →1→ ② →2→ ③

→ x GRADIENTS ⎫
↑ y GRADIENTS ⎬ g
○ PHASE POINTS   x

-1 1
-1 1
-1 1
-1 1
-1 1
-1 1
A
-1
-1
1
-1
-1 1
-1 1
-1 1

$g = Ax + n$

ESTIMATE $\hat{x} = Bg$

F-21

SHARED APERTURE OPTICAL DEVICE
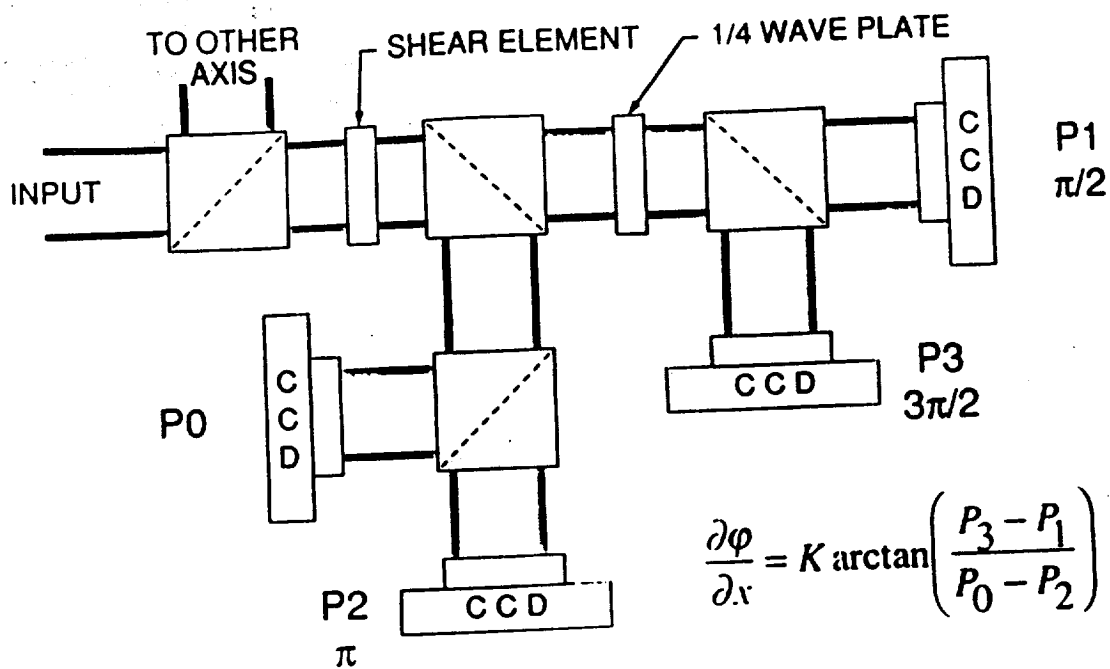
CONCEPT
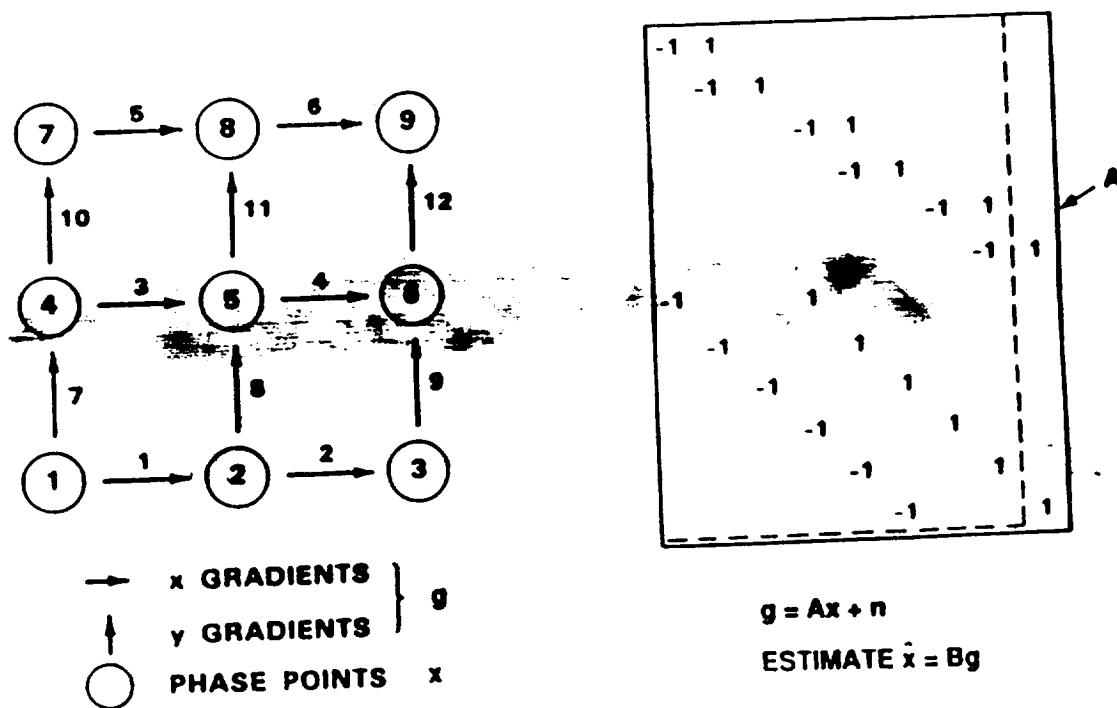
COOLED PRIMARY ELEMENT

- SAOD BUILT BY UTOS

- TWO GRATING SYSTEM TO SPLIT 0.6 TO 0.9 μm BEAM FROM 3.8 μm HEL BEAM

- WATER COOLED PRIMARY

- 40-50% EFFICIENCY AT $\lambda = 0.755$ μm

- SYSTEM COMPLETED, CHARACTERIZED AND TESTED UNDER 25% MIRACL POWER

Prepared by

TECHNOLOGY DEVELOPMENT FOR LARGE BEAM DIRECTORS

- PRELIMINARY DESIGN & SPECIFICATIONS GENERATED FOR GBFEL TIE 3.5-m BEAM DIRECTOR

- EXTENSIVE MODELING AND COMPONENT DEVELOPMENT OF BEAM-PATH CONDITIONING SYSTEMS PERFORMED IN SUPPORT OF ARMY BMD/ASAT PROGRAMS
  - VACUUM-INTERFACE AND EXIT WINDOWS
  - AIR CURTAINS
  - BEAM-EXPANDER CONDITIONING
  - BOUNDARY-LAYER CONTROL

- STUDY OF FEASIBILITY OF BUILDING LARGE (≥10m) BEAM DIRECTORS COMPLETED IN FY 89
  - CRITICAL TECHNOLOGIES IDENTIFIED
  - FEASIBLE TO BUILD TO TENS OF METERS

- PHASING OF SEGMENTED MIRRORS IN PRESENCE OF TURBULENCE DEMONSTRATED IN SCALED LABORATORY EXPERIMENTS UNDER INNOVATIVE RESEARCH PROGRAM

ADVANCED BEAM DIRECTORS

BEAM PATH-CONDITIONING
LAB TEST BED

SCHEMATIC OF HELIUM SYSTEM
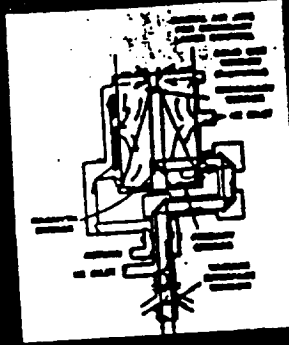
VERY LARGE BEAM DIRECTORS

ELEVATION OVER AZIMUTH LASER BEAM DIRECTOR
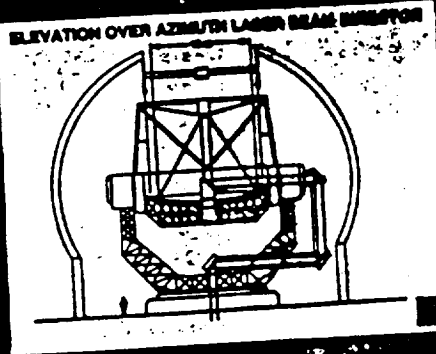
PHASING LARGE TELESCOPE SEGMENTS

LASER POWER TRANSMISSION TO MOON

BEACON

10 m APERTURE

TO TILT
CORRECTOR

TRACKER

RECONSTRUCTOR

WAVEFRONT
SENSOR

BEACON
RADIATION

BEAM
DIRECTOR

HIGH POWER LASER (FEL)

APERTURE
SHARING
ELEMENT

DEFORMABLE
MIRROR

TILT CORRECTOR

LUNAR STATION

RADIUS OF UNCORRECTED BEAM
5000 m
INTENSITY ~ 0.4 W/m²

COLLECTOR ARRAY
80 m

ATMOSPHERE
PROBE BEACON
(Laser or Retroreflector)

~ 90%
DIFFRACTION
LIMITED
POWER
COLLECTED

DIFFRACTION
LIMITED
BEAM DIAMETER
(~ 63% ENERGY)
BEAM INTENSITY ~4kW/m²

90 m

~ 2500 m

POWER
CONDITIONING

LOAD
(1 MW)

STORAGE

FOR GROUND LASER
OUTAGES (Clouds)

HIGH-POWER LASER OPTIONS

⇒ **FREE-ELECTRON LASER:** TUNABLE (VISIBLE TO IR)
SCALABLE TO HIGH POWER
DESIGNS FOR 10 MW EXIST
HIGH EFFICIENCY PROJECTED (~10%)

DF CHEMICAL LASER: AT 3.8 μm – LARGE APERTURE REQUIRED
MEGAWATTS POSSIBLE
ENERGY CONVERSION? (PROPULSION CANDIDATE)
BEAM CONTROL EASIER???

O_2I CHEMICAL LASER: AT 1.3 μm – APERTURE FEASIBLE
POWER SCALING PROBLEMATIC

MICRO-CHIP LASERS:
(SOLID STATE) WAVELENGTHS IN NEAR IR (DOUBLE TO VISIBLE)
INDIVIDUAL LASERS DEMONSTRATED
SCALING POTENTIAL GREAT
COMPACT, RUGGED, INNOVATIVE PHASE CONTROL

ATMOSPHERIC-COMPENSATION REQUIREMENTS

- TURBULENCE REQUIRES HIGH SPATIAL AND TEMPORAL
FREQUENCY CORRECTION CAPABILITY:
    - UNCORRECTED BEAM SPREAD ~100 XDL (intolerable)
    - TILT CORRECTION
        ~2 μrad STANDARD DEVIATION
        ~10 Hz BANDWIDTH (other tracking errors will dominate)
    - HIGH-ORDER PHASE CORRECTION
        ~3 WAVES rms DEVIATION (at 1-μm wavelength)
        $\leq$100 Hz BANDWIDTH
        (Requires beacon-probe repetition rate of >1 kHz)

- THERMAL BLOOMING CORRECTION REQUIREMENTS ARE
SUBSUMED IN THOSE OF TURBULENCE, PROVIDED AN
OPTIMAL PROPAGATION WAVELENGTH IS CHOSEN.

ATMOSPHERE COMPENSATION REQUIREMENTS

TURBULENCE COHERENCE DIAMETER DEPENDENCE ON WAVELENGTH AND ZENITH ANGLE
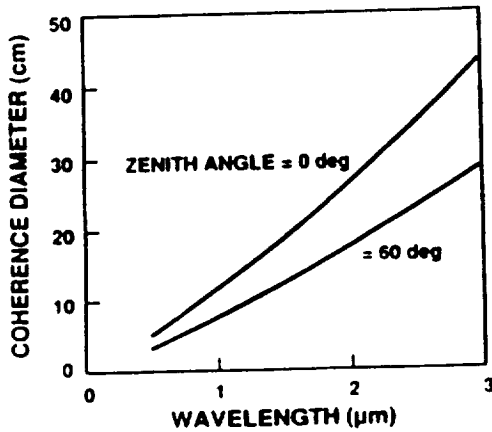
DEPENDENCE OF FRACTION OF TOTAL LASER POWER ON MOON COLLECTED BY ARRAY ON ACTUATOR SPACING IN DEFORMABLE MIRROR
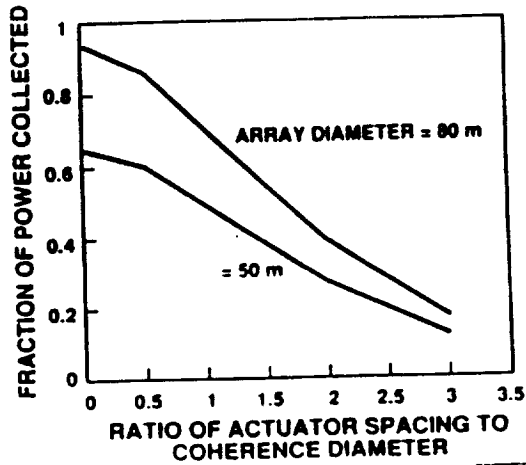
NUMBER OF ACTUATORS
WAVELENGTH DEPENDENCE
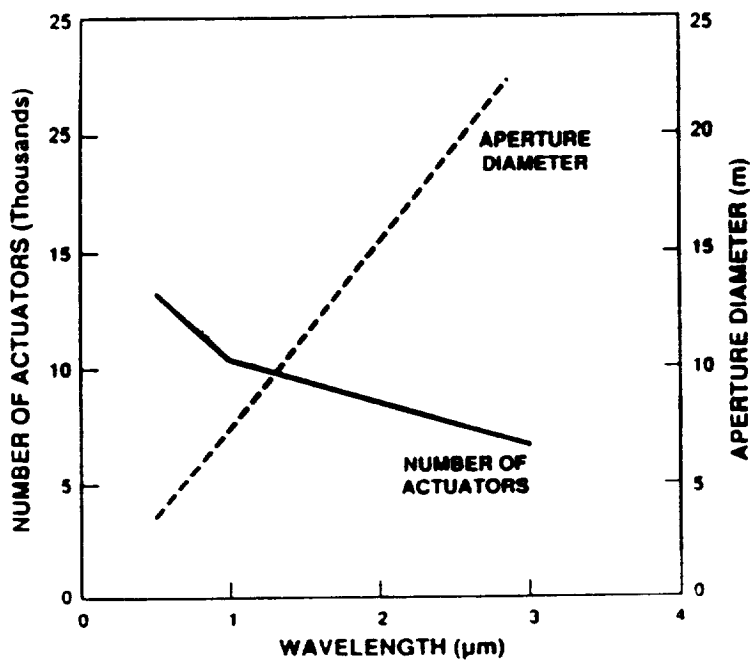
CURVES BASED ON:

70% OF POWER INTO 80 m COLLECTOR

ACTUATOR SPACING = COHERENCE DIAMETER

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WAVEFRONT SENSOR OPTIONS

- **HARTMANN**
    - CHARACTERIZED BY ARRAY OF POSITION-SENSING DETECTORS
    - USED IN RECENT PROGRAMS – EXPERIENCE BASE SUBSTANTIAL
    - REQUIRES 4x4 PIXEL ARRAY PER SUBAPERTURE
    - FOR 10^4 SUBAPERTURES: 420x420 CCD (exists)
    - SUBSTANTIAL PARALLEL ARCHITECTURE

- **SHEARING INTERFEROMETER**
    - USED LESS THAN HARTMANN
    - ADVANTAGES ARE LARGER DYNAMIC RANGE, LOWER NOISE
    - DISADVANTAGE IS LARGER NUMBER OF CAMERAS
    - FOR 10^4 SUBAPERTURES: 4 CCDs OF 100x100 EACH

NOTE: BOTH APPROACHES BASED ON LINCOLN LABORATORY CCDs...
THINNED, BACK-SIDE ILLUMINATED, P+-DOPED, w/LOW-NOISE READ-OUT FETs
QUANTUM EFFICIENCY ~90%
NOISE LEVEL ~30 ELECTRONS/PIXEL AT 3 MPIXEL/SEC READ OUT

BEACON OPTIONS

- **ASSUMPTIONS AND REQUIREMENTS:**
    - 10^4 SUBAPERTURES
    - 10^3 UPDATES/SECOND
    - 10^3 PHOTONS/SUBAPERTURE/UPDATE (at WFS focal plane)

- **EARTH-BASED LASER – LUNAR RETROREFLECTOR (examples):**

COMPENSATED	POWER	APERTURE	RETRO ARRAY SIZE	# RETROS
NO	10 KW	1 M	5 M	1600
YES	500 W	1 M	2 M	250

- **MOON-BASED LASER**
    - POWER = 1 W, APERTURE = 1 cm
    - POINTING REQUIREMENT 0.1 mrad

- **SYNTHETIC BEACON**
    - COMPLICATION SEEMS UNNECESSARY

RECONSTRUCTOR SCALING

- NUMBER OF COMPUTATIONAL OPERATIONS SCALES AS $\geq n^4$ FOR MATRIX-BASED RECONSTRUCTORS (n = subapertures/dia.)

- MULTIGRID APPROACH SCALES ONLY AS $n^2 \log n$

- PARALLEL-PROCESSOR ARCHITECTURE READILY SCALES TO LARGE SYSTEMS

PARAMETER	MATRIX	MULTIGRID
DIAMETER	10 m	10 m
SUBAPERTURES (n)	102	102
TOTAL SUBAPERTURES	8192	8192
MULTIPLY/ACCUM.	1.7×10^8	7.5×10^5
PROCESSORS	20808	3414
RACKS	160	8

SOURCES OF ADAPTIVE OPTICS ERROR

- FITTING
    - WITH FINITE RESOLUTION, A DEFORMABLE MIRROR ONLY APPROXIMATES REQUIRED CONJUGATE PHASE

- POINTING
    - IDEAL POINT-AHEAD BEACON LOCATION DEPENDS ON ORBITAL POSITION OF MOON, SO LOCATION OF STATIONARY BEACON IS NOT IDEAL AT ALL TIMES

- BANDWIDTH
    - THE DYNAMIC ATMOSPHERE MOVES A LITTLE DURING A COMPENSATION UPDATE

- SCINTILLATION
    - ADAPTIVE OPTICS CORRECTS PHASE, NOT AMPLITUDE

- SIGNAL-TO-NOISE
    - A WAVEFRONT SENSOR IS LIMITED BY THE BEACON SIGNAL RECEIVED

BEAM-CONTROL SYSTEM — STRAWMAN DESIGN

- "CONVENTIONAL" 10-M-DIAMETER BEAM DIRECTOR

- ADAPTIVE OPTICS FOR ATMOSPHERIC COMPENSATION IN UNEXPANDED LEG OF BEAM DIRECTOR

- ADAPTIVE OPTICS:
    - CONTINUOUS-FACESHEET DEFORMABLE MIRROR (segmented back up):
        HIGH REFLECTIVITY COATING, COOLED SUBSTRATE
        10^4 ACTUATORS
        100-Hz BANDWIDTH
    - HARTMANN WAVEFRONT SENSOR (shearing interferometer back up)
        10-kHz FRAME RATE
        LOW-NOISE, HIGH-QE CCD FOCAL PLANES
    - BEACON
        LASER-ILLUMINATED RETRO ARRAY (compensated)
    - RECONSTRUCTOR – RELAXATION METHOD DESIGN

- POINTER/TRACKER:
    - SEPARATE TILT CORRECTING MIRROR
    - 4 μrad RMS @ 100-Hz BANDWIDTH (conservative design)

ADAPTIVE OPTICS ERROR BUDGET

$\lambda = 1\mu m$, $r_o = 9.6$ cm AND $\theta_o = 15$ μrad AT ZENITH,
ACTUATOR SPACING 10cm, BANDWIDTH 100 Hz, WIND 6 m/s,
RETRO ARRAY AT MEAN POINT-AHEAD LOCATION
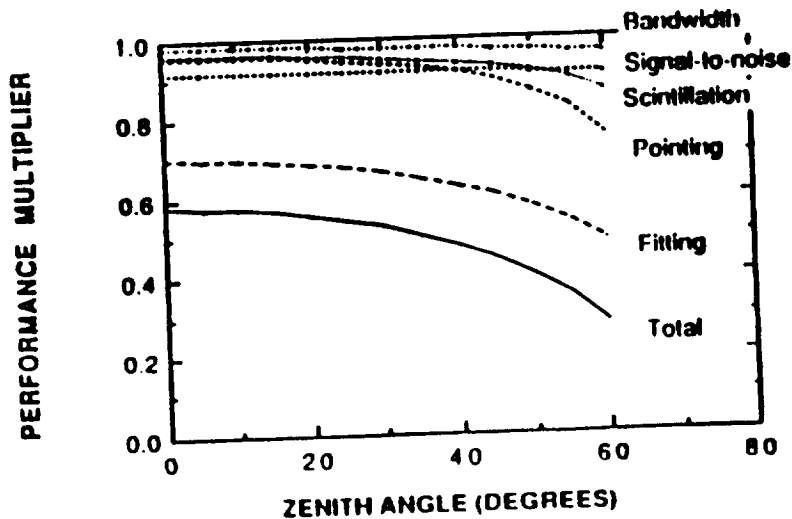
BASELINE SYSTEM
REPRESENTATIVE POWER BUDGET

LASER OUTPUT	**11 MW**	
OPTICS TRANSMISSION		0.9 X
POWER OUT OF APERTURE	<u>10 MW</u>	
ATMOSPHERIC TRANSMISSION		0.9
ATMOSPHERIC COMPENSATION		0.5
COLLECTOR GEOM. EFFICIENCY		0.9
ARRAY ELECTRICAL EFFICIENCY		0.5
ELECTRICAL POWER OUT	**2 MW**	
POWER CONDITIONING		0.8
ELECTRICAL DISTRIBUTION		
LOAD	1 MW	
STORAGE (0.3 efficiency)	0.6 MW →	0.18 MW (per earth station)

4 EARTH STATIONS LOCATED NEAR EQUATOR SHOULD PROVIDE CONTINUOUS 1-MW ELECTRICAL DEMAND POWER. (Assumes weather power outage ~10%, and requires 1-2 stations illuminating array simultaneously.)

CONCLUSION

A BEAM-CONTROL SYSTEM FOR EFFICIENT TRANSMISSION OF LASER POWER FROM EARTH TO THE MOON CAN BE BUILT:

- TECHNOLOGY REQUIREMENTS AND PHYSICS LIMITATIONS ARE WELL UNDERSTOOD IN SMALL-SCALE EXPERIMENTS
- GROUND-TO-SPACE HIGH-POWER LASER PROPAGATION EXPERIMENTS ARE REQUIRED
- ADDITIONAL HARDWARE SCALING IS REQUIRED BEYOND STATE OF THE ART

INITIATIVE FOR THE 21ST CENTURY:
ADVANCED SPACE POWER AND PROPULSION BASED
ON LASERS

B. G. Logan
Lawrence Livermore National Laboratory
Livermore, CA

NASA-Lewis Research Center
Cleveland, OH
April 25-26, 1988

February 1, 1989

Lawrence
Livermore
National
Laboratory

INITIATIVE FOR THE 21st CENTURY:
ADVANCED SPACE POWER AND PROPULSION
BASED ON LASERS*

B.G. Logan

Lawrence Livermore National Laboratory

LOW-COST ACCESS TO THE INNER SOLAR SYSTEM

LAWRENCE LIVERMORE LABORATORY

1985 1990 1995 2000 2005 2010 2015 2020 2025 2030 2035

HIGHWAY TO SPACE

- LOW-COST CARGO TRANSPORT VEHICLE

  FIRST LAUNCH ▲

- LOW-COST PASSENGER TRANSPORT VEHICLE

  ROCKET OR SPACEPLANE ▲

- TRANSFER TO DESTINATIONS BEYOND LOW EARTH ORBIT

  TRANSFER VEHICLE
  GROUND-SPACE BASED ▲ ▲ BASED ▲ ▲ SOLAR ELECTRIC TRANSFER VEHICLE

- EARTH SPACEPORT

  IOC SPACE STATION ▲ INITIAL SPACEPORT ▲ FULL SPACEPORT ▲

BRIDGE BETWEEN WORLDS

- LUNAR OPERATIONS

  ROBOTIC LUNAR RETURN ▲ HUMAN OUTPOST ▲ PILOT PROPELLANT PLANT ▲ PROPELLANT PRODUCTION ▲ MANUFACTURING

- TRANSPORTATION TO NEW WORLDS

  SMALL NUCLEAR CARGO TRANSFER ▲ MARS CREW TRANSFER VEHICLE ▲ LARGE NUCLEAR CARGO TRANSFER ▲ ▲ CYCLING SPACESHIPS ▲

- DISTANT SPACEPORTS

  IOC SPACE STATION ▲ VARIABLE G FACILITY ▲ LUNAR SPACEPORT ▲ LIBRATION POINT SPACEPORT ▲ MARS SPACEPORT ▲

- MARS OPERATIONS

  ROBOT PLANT OUTPOST ▲ HUMAN OUTPOST ▲ INITIAL BASE ▲ FULL BASE ▲

1985 1990 1995 2000 2005 2010 2015 2020 2025 2030 2035

Source: The Report of the National Commission on Space, 1987

LAWRENCE LIVERMORE LABORATORY
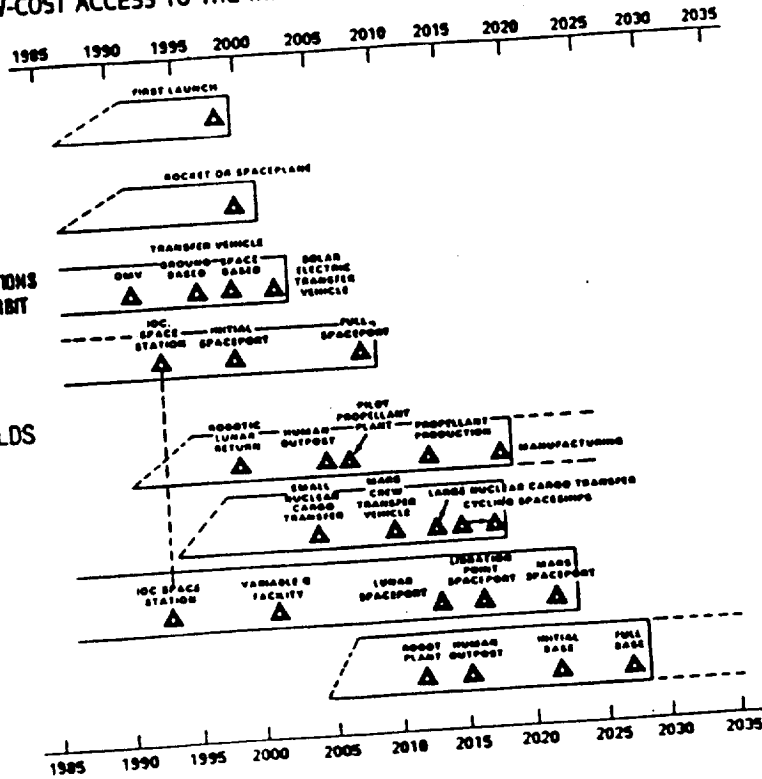
COST OF PROPOSED US SPACE PROGRAM

- CONSTANT FY 86 DOLLARS
- GNP GROWTH AT 2.4% PER YR FROM 1986
- US PORTION SHOWN (75% OF TOTAL PROGRAM COSTS)

U.S. GROSS NATIONAL PRODUCT ANNUAL DOLLARS, TRILLIONS

COST OF PROGRAM ANNUAL DOLLARS, BILLIONS

CURRENT

US GROSS NATIONAL PRODUCT

APOLLO PROGRAM

PROGRAM COST

HISTORICAL DATA   PROJECTED DATA

1960 1970 1980 1990 2000 2010 2020 2030

Source: The Report of the National Commission on Space, 1987

G-3
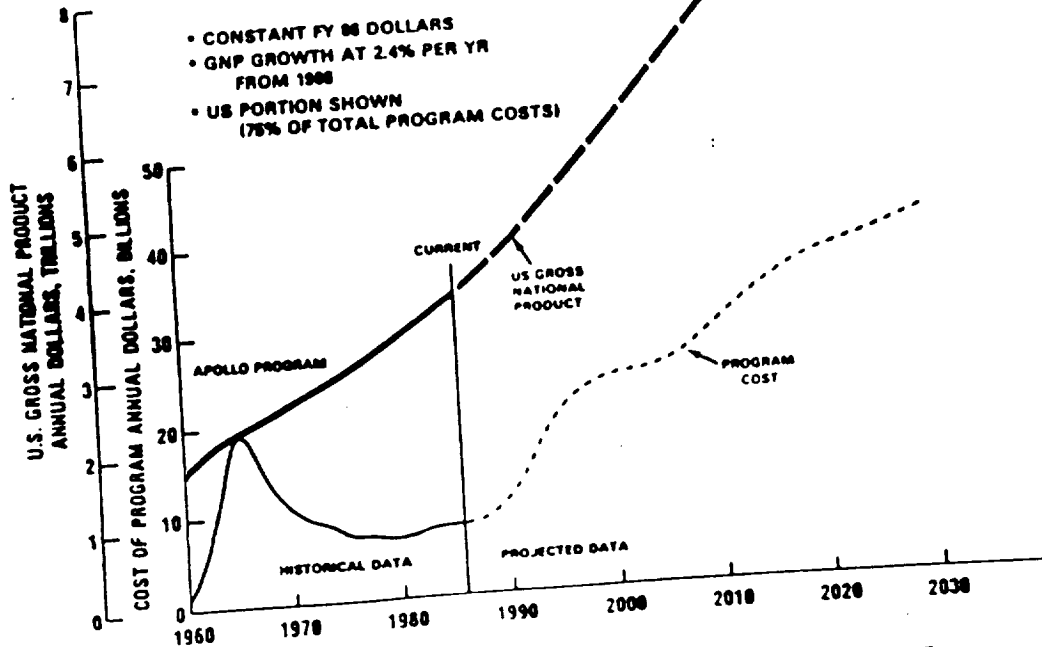
THE BASIC PRINCIPLE OF LASER POWER/PROPULSION IS SOUND, HAS
ROBUST ECONOMIC ADVANTAGE, AND HAS DIVERSE SPACE APPLICATIONS

- THE FUNDAMENTAL LEVERAGE OF REMOTE LASER-POWERING OF
  SPACECRAFT LIES IN THE DRAMATIC REDUCTION OF NON-PAYLOAD
  MASS AND PROPELLANT CONSUMPTION FOR HIGH $\Delta V/\Delta T$ MISSIONS,
  VIA HIGHER SPECIFIC IMPULSES >> CHEMICAL, AND:

  - REDUCTION OF STRUCTURAL MASS
    (USING LASER-ABLATION DRIVE)

  - REDUCTION OF ON-BOARD POWER-SUPPLY MASS
    (USING LASER-ELECTRIC DRIVE)

→ MORE THAN 10X PAYLOAD DELIVERY PER DOLLAR

- SUCCESS DOES NOT DEPEND EXCLUSIVELY ON A SINGLE APPROACH
  OR SET OF COMPONENTS--THERE ARE A VARIETY OF LASERS,
  WAVELENGTHS, TRANSMISSION SYSTEMS, AND DRIVE METHODS
  WHICH CAN WORK, AND IN DIFFERENT COMBINATIONS.

- GROUND-BASE LASERS WITH SPACE-RELAY MIRRORS CAN PERFORM A
  VARIETY OF TASKS--TRANSMISSION OF ELECTRICAL POWER TO
  SATELLITES, SPACE-STATIONS, AND LUNAR BASES, AND
  PROPULSION OF DIFFERENT VEHICLES.

- LOW COST DEVELOPMENT PATH--PHASEABLE IN LOW RISK STEPS,
  ALWAYS LESS THAN 2% OF THE SPACE PROGRAM BUDGET; USEFUL
  10 MW GBL SYSTEMS << 1 NEW SHUTTLE COST.

G-4

REMOTE LASER-POWERED SPACECRAFT ALLOW HIGHER PAYLOAD FRACTION M_{PAY}/M_I (PAYLOAD/INITIAL MASS) BY INCREASING EXHAUST VELOCITY V_{EX}, AND BY REDUCING VEHICLE STRUCTURAL MASS OR POWER-SUPPLY MASS

INITIAL MASS $M_I = M_F \, EXP(\Delta V/V_{EX})$

FINAL MASS $\quad M_F = M_{PAY}$ (PAYLOAD)
$\qquad\qquad\qquad + F_S \, M_I$ (STRUCTURE, TANKS, MOTORS)
$\qquad\qquad\qquad + \alpha_E \, P_E$ (POWER SUPPLY)

USING $P_E = \dot{M} \, V_{EX}^2 \, (2 \, \eta_E \eta_{JET})^{-1}$

AND $\dot{M} = (M_I - M_F)/\Delta T \approx M_I/\Delta T$, $[EXP(\Delta V/V_{EX}) \gg 1]$

OBTAINS $\dfrac{M_{PAY}}{M_I} \approx EXP\left(-\dfrac{\Delta V}{V_{EX}}\right) - F_S - \dfrac{\alpha_E \, V_{EX}^2}{2 \, \eta_E \eta_{JET} \Delta T}$

→ WHEN $EXP(-\Delta V/V_{EX})$ IS SMALL (LARGE ΔV), STRUCTURE FRACTION F_S MUST BE MINIMIZED (EVEN WHEN $\alpha_E = 0$).

→ LASER-ABLATION DRIVE MINIMIZES F_S - ELIMINATES STRUCTURE, TANKS AND MOTORS.

→ WITH LASER-ELECTRIC DRIVE, SPECIFIC MASS $\alpha_E = (KG/KW_E$ FOR POWER SUPPLY) CAN ALSO BE SMALL, AND α_E MUST BE SMALL WITH LARGE V_{EX} (FOR HIGH SPECIFIC IMPULSE), AND WITH LIMITS ON ΔT FOR MANNED MISSIONS FORCED BY RADIATION-DOSE CONSTRAINTS.

→ LASER--PHOTOCELL α_E CAN BE 1 TO 2 ORDERS OF MAGNITUDE SMALLER THAN SOLAR-ELECTRIC α_E OR NUCLEAR ELECTRIC α_E.

THE TRANSMISSION RANGES OF GENERIC LASER-PROPULSION METHODS
ARE LIMITED BY DIFFRACTION AND CAPABILITY OF FOCUSING TO THE
REQUIRED LASER DRIVE INTENSITIES.

- LASER - ICF DRIVE REQUIRES FOCUSED INTENSITIES
  $\phi \gtrsim 10^{14} W/cm^2$

  - → LASER-TO-FOCUS RANGE LIKELY SHORT ENOUGH TO REQUIRE
    ON-BOARD LASERS (VISTA CONCEPT)

- LASER - ABLATION DRIVE REQUIRES FOCUSED INTENSITIES
  $\phi \gtrsim 10^8 W/cm^2$

  - → GROUND-BASE LASER RANGE TO VEHICLE FOCUS LIMITED TO
    $\lesssim 10^3$ KM ($\lesssim 10^4$ KM WITH FOIL CONCENTRATORS) (KANTROWITZ
    CONCEPT)

- LASER - ELECTRIC DRIVE (PHOTOCELL RECEIVERS) REQUIRES
  FOCUSED INTENSITIES $\phi \gtrsim 300$ W/cm^2, FOR 10^{-3} DUTY PULSED
  LASERS AND $\alpha_E < 0.5$ KG/KW$_E$ (>10X MORE POWER/AREA THAN
  SOLAR-CELLS).

  - → LASER-TO-FOCUS RANGES APPROXIMATELY $\lesssim 3 \times 10^5$ KM
    (0.8 μ) (EARTH → MOON) TO 10^7 KM (200-2000 Å, UV),

  OR $\lesssim 3 \times 10^6$ KM (0.8 μ) TO 10^8 KM (MOON → MARS)
    (200-2000 Å, UV) USING FOIL CONCENTRATORS.

  - → LOWEST INTENSITY REQUIREMENT → GREATEST LASER-TO-FOCUS
    TRANSMISSION RANGE USING LOW-MASS FOIL CONCENTRATORS.

Table 4 Characteristics for Electromagnetic Beam Power Transmission in Space

Assume phase-corrected transmitter mirrors or phased arrays to achieve diffraction-limited optics:

Collector (receiver) diameter

$$D_c = 2.44 \, \lambda \, Z \, / \, D_t$$

where λ = electromagnetic wave length (m)

Z = transmitter to receiver distance (m)

D_t = effective transmitter aperture (m)

Power Transmission Examples	Transmission Distance Z (km)	Wavelength λ	Transmitter Diameter D_t (m)	Collector (Receiver) Diameter D_c (m)
Solar Power Satellite GEO to Earth	3.5×10^4	12 cm (2.4 GHz)	1000	10,000
Shortest Microwave λ for low atmospheric attenuation, Earth to GEO	3.5×10^4	3 mm (94 GHz)	500	500
Infrared Laser Earth to GEO	3.5×10^5	800 nm	0.5	150
Infrared Laser GEO to Moon	3.8×10^5	800 nm	3.7	200
UV Laser GEO to Moon	3.8×10^5	200 nm	1.9	100
UV Laser Moon to Mars	8×10^7	200 nm	100	390

AN ECONOMICAL EARTH-MOON TRANSPORTATION SYSTEM BASED ON PULSED PLASMA GUNS REMOTELY POWERED BY FREE-ELECTRON-LASERS

LAWRENCE LIVERMORE LABORATORY

Cycling Lunar Lander

Lunar Base

MOON

Low Lunar Orbit

Inflatable Foil Mirror

Monthly-Cycling Manned Lunar Shuttle

Shielded Crew Cabin

NASA

Propellant

Photocell Receiver

Pulsed Plasma Gun

Propellant Cargo

0.3 MW Solar Cell Arrays

Bi-Annual-Cycling Unmanned Lunar Ferry

GEO Relay Mirror

Geosynchronous Earth Orbit

Low Earth Orbit

Uplink Mirror

Manned Earth Shuttle

EARTH

Ground-Based Free Electron Laser

G-8

Component technologies for a high power Free-Electron Laser

90 A-0986-2336

Microwave Pulse
from FEL

$\lambda 12$
$\simeq 1.5mm$

Half-Wavelength
Dipole Antenna

Pulsed DC

Field Emission
Diode

To PPG via Strip
Transmission lines

Equivalent Circuit

Top View
of Rectenna

(a) FEL Microwave Rectenna (FELMR)
(thin wafer VLSI manufacture $\simeq 1$ kg/m^2)
max $\eta_{conv} = 0.80$

$h\nu$

Pulsed DC

Substrate

(b) FEL Photocell Converter (FELPC)
(thin wafer VLSI manufacture ≈ 1 kg/m^2)
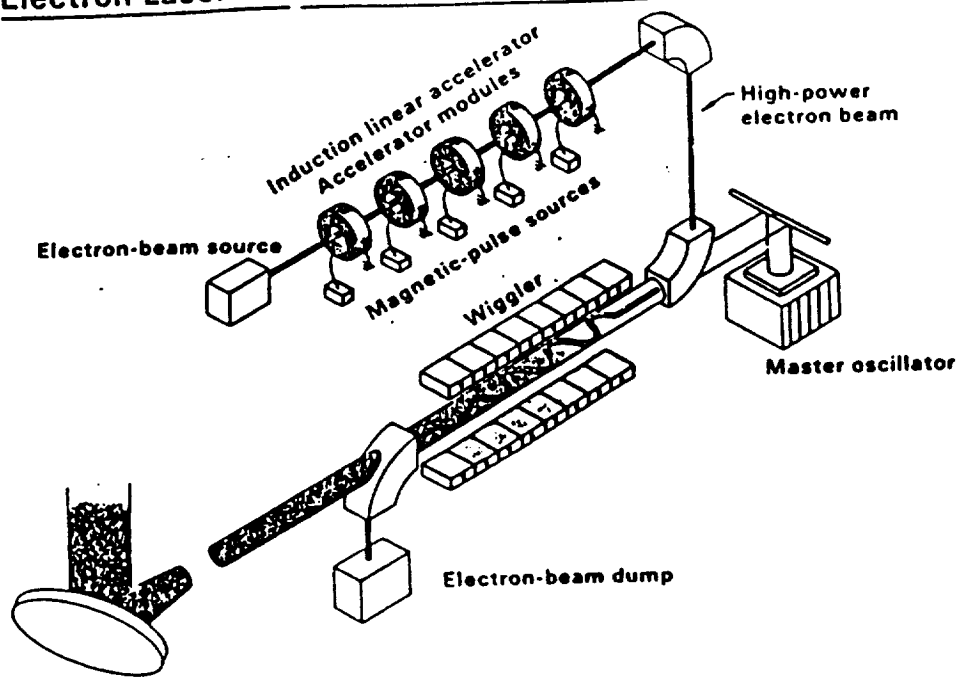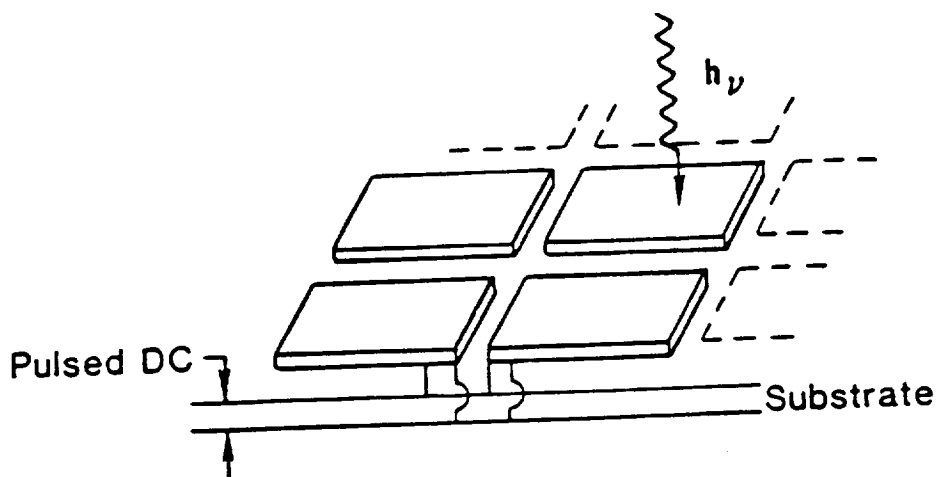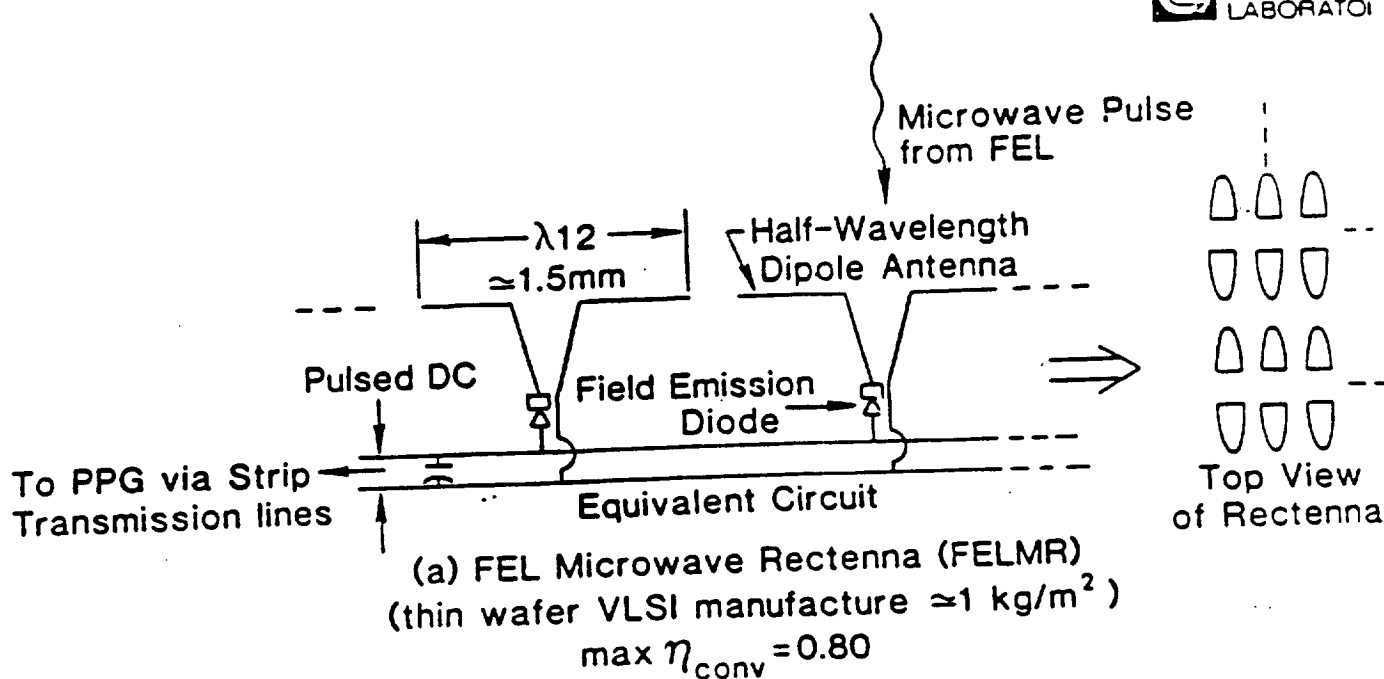
- infrared $\lambda = 8000$ Å, silicon, 1.2 volt band gap
$T_{max} \simeq 300^0$ K

- uv $\lambda = 2000$ Å, diamond, 5 volt band gap
$T_{max} \simeq 1200^0$ K

Max $\eta_{conv} \simeq 0.67$

Panel-convertor approaches for (a) microwave
FEL beams and (b) infrared /uv FEL beams

Table 5 Comparison of receivers/electrical conversion characteristics for FEL-beam-powered, electric-propulsion spacecraft

Parameters	Solar cells (non-FEL)	Infrared silicon photocell	UV, diamond photocell	Microwave rectenna
Average electrical power/area (kWe/m^2)	0.2	2.0	20	20
Wavelength	Solar spectrum	800 nm	200 nm	3 mm
Maximum Conversion Efficiency η_{conv}	0.15	0.67	0.67	0.80
Waste Heat Radiated (kW_{th}/m^2)	1.4	1.0	10	5
Operating Temperature $T, {}^\circ K ({}^\circ C)^*$	$400^\circ K$ $(130^\circ C)$	$370^\circ K$ $(100^\circ C)$	$660^\circ K^{**}$ $(385^\circ C)$	$555^\circ K^{**}$ $(282^\circ C)$
Panel $\dfrac{mass}{area}$ kg/m^2 ***	1	1	1	1
Panel specific mass (nominal) α_e	5	0.5	0.05	0.05

$$\alpha_e = \frac{k_g}{kWe}$$

* T at which $5.7 \times 10^{-8} (T^\circ K)^4 \times 1$ side = waste heat radiated in W/m^2.

** Max T may exceed $1000^\circ K$ with diamond semiconductor photocell, or with field-emission microdiodes for rectennas.

*** All cases VLSI-manufactured wafers < 100 microns thick.

Parameter	Microwave GBFEL	Infrared GBFEL, GEOFEL	UV GEOFEL
Output wavelength	3 mm (94 GHz)	800 nm	200 mn
Average power output/unit (MW)	20	10	10
# of units per system	4	$\leq$ 8 - GBFEL 1 - GEOFEL	1 GEOFEL
Type of FEL accelerator/ wiggler	single beam, superconducting wiggler, waveguide	two-beam accelerator, superconducting wiggler, waveguide	two-beam accelerator superconducting wiggler, waveguide
E_{beam} (1) (MeV)	7	3.5 (for 10GHz) driver	3.5 (for 10GHz) driver
[E_{beam} (2) (MeV)]	[NA]	[310]	[500]
I_{beam} (1), (KA)	8	8	8
[(2), (KA)]	[NA]	[0.08]	[0.05]
Pulse length (nsec)	50	50	50
Pulse repetition rate (kHz)	20	20	20
Wiggler Field B_{w1} (T)	0.5	0.5	0.5
[B_{w2} (T)]	[NA]	[1.0]	[1.5]
Wiggler wavelength λ_{w1} (m)	0.1	0.1	0.1
λ_{w2} (m)	[NA]	[5×10^{-2}]	[3.3×10^{-2}]
Accelerator + wiggler length L_1	7 + 5	7 + 5	7 + 5
L_2	[NA]	[3 + 5]	[5 + 5]
Overall efficiency MWe to MWγ out	0.28	0.25	0.25

* May require three beam tubes, wigglers per ferrite core (Barletta)

** $\eta_{wiggler}$ = 0.40 (tapered wiggler), $\eta_{beam\ 1}$ = 0.70, $\eta_{beam\ 1\ +\ beam\ 2}$ = 0.9

COAXIAL PLASMA GUNS IN GENERAL HAVE ACHIEVED COMBINATIONS OF HIGH SPECIFIC IMPULSE AND HIGH JET EFFICIENCY MORE EASILY IN A PULSED-MODE THAN IN STEADY-STATE.

- EMPIRICALLY, BEST PERFORMANCE WITH PLASMA GUNS HAS BEEN MADE WITH SHORT ($\lesssim$ FEW MICROSECOND) PULSES.

- DIRECT-CONVERSION OF PULSED-LASER POWER WITH PHOTOCELLS COULD MAKE A NATURAL COMBINATION WITH PULSED-PLASMA GUNS, MINIMIZING POWER-CONDITIONING EQUIPMENT ON-BOARD SPACECRAFT.

- THE PRINCIPAL DEVELOPMENT REQUIRED WOULD BE EXTENSION OF PULSED PLASMA GUN OPERATION TO HIGH PULSE-REPETITION RATES (SEVERAL KILOHERTZ), AND USE OF ELECTRODES AS REPLENISHABLE PROPELLANT (LIQUID-METAL-WETTED ELECTRODES, OR REPLACEABLE SOLID CARTRIDGE ELECTRODES).

- SCALING OF I_{SP} AND η_{JET} WITH GUN PARAMETERS NEEDS BETTER CHARACTERIZATION TO ALLOW TRIP OPTIMIZATION (VARIABLE I_{SP}).

A COMPARATIVE ANALYSIS SHOWS THAT LASER-POWERED-PHOTOCELL-
PLASMA-GUN DRIVE ALLOWS THE LOWEST-COST PROPULSION FOR MANNED
MISSIONS TO DISTANT DESTINATIONS (E.G., TO MOON OR MARS).

- PLASMA GUNS ARE PROVEN TO ATTAIN OPTIMUM SPECIFIC
  IMPULSES (2000-3000 SEC)>>CHEMICAL I_{SP}

  → REDUCES ENORMOUS PROPELLANT COST FOR LUNAR/MARS
    MISSIONS.

- LASER-PHOTOCELL-GUN SPECIFIC MASS α_E (KG/KW$_E$) CAN BE
  SMALLER THAN SOLAR-ELECTRIC OR NUCLEAR-ELECTRIC α_E BY
  1 TO 2 ORDERS OF MAGNITUDE → BEATS SOLAR/NUCLEAR
  COMPETITORS FOR MANNED MISSIONS WHERE TRIP TIMES ARE
  CONSTRAINED BY RADIATION DOSE.

- LASER AND OPTICS CAPITAL COSTS ARE MUCH REDUCED WITH
  LASER-ELECTRIC DRIVE COMPARED TO LASER-ABLATION DRIVE,
  DUE TO 5-6 ORDERS OF MAGNITUDE LOWER LASER INTENSITIES
  REQUIRED AT LONG RANGE. FOR SHORT RANGE LAUNCH TO LEO,
  LASER-ABLATION DRIVE IS UNIQUE FOR LOWEST COST COMMODITY
  (PROPELLANT) TRANSPORT TO LEO.

−

+

Coax (or Flat Plates)
Transmission lines to Matched
Pulsed Laser Receiver (no switches)

Insulator and support

~0.5m

I I

Anode +

Liquid Propellant
to porous Cathode

B_θ

J_r Cathode −

30° plasma
plume

Gun Trigger
(Spark Plug)

~170 eV
mean Na, K ion
energy

Liquid Metal-Wetted
Porous Molybdenum
Gun Barrel Surfaces

Liquid Metal Propellant (NAK)
to porous Anode

Open-Mesh Radial Transmission line for
access to Space Vacuum, blackened for
Waste Heat Radiation at ~1000°K

Schematic cutaway view of a pulsed plasma gun for space vehicle propulsion

Table 10 Suggested parameters for pulsed-plasma gun (PPPG) rocket motors
(Fig. 13) propelling the Manned Lunar Shuttle

Parameter	PPG	Typical present single-pulse guns[*]
Pulse length	2 μ sec	2 - 5 μ sec
Current	15 kA	10 - 500 kA
Voltage	10 kV	5 - 20 kV
Gun recovery time	< 50 μ sec	< 50 μ sec
Pulse repetion rate[**]	20 kHz	single pulse
# pulses per electrode lifetime	$\geq 10^{10}$ needed	$10^4 - 10^5$ (max. achieved)
plasma species[***]	Na^+, K^+ ions	H^+, D^+, He^+, etc.
# of fast ions/pulse	2×10^{17} ions at 5 keV	$10^{17} - 10^{18}$ at 5 - 10 keV
# of slow ions/pulse	3.5×10^{18} at 100 eV	$10^{18} - 10^{19}$ at 50 - 200 eV
$\bar{v}_{exhaust}$	3×10^4 m/sec	$10^5 - 10^6$ m/sec (D^+)
plume half angle	$30°$	$20 - 45°$
Efficiency $\frac{E_{plasma}}{\Delta E_{capacitor}}$	0.45 (fast ions) 0.90 (fast + slow ions)	0.3 - 0.5 (measured for for fast ion only)
Ave. thrust	115 Newtons	small
Ave. power	6 MWe	small
Motor Weight (PPG)	300 kg	100 - 200 kg

[*] reference Krall and Trivelpiece, "Principles of Plasma Physics", McGraw Hill 1973 p. 30-32.

[**] to match pulsed FEL repetition rate.

[***] many other propellants (gaseous, liquid, solid) may be feasible, including cycling cartridges of consumable solid electrodes as propellant.

High-Repetition-Pulsed Lasers and Photovoltaic Receivers may be Useful for Pulsed Plasma-Thruster Power

- Long electrode life may require keeping the average plasma discharge and power density <u>below</u> some <u>maximum</u>, while ...

- High plasma exhaust velocity ($I_{sp} > I_{sp}$, minimum) may require plasma discharge current and power density <u>above</u> some <u>maximum</u>.

- Conflict in the above two demands may be met by scaling the gun electrode area up to keep <u>average</u> heat loads low, while delivering the thruster power in a series of high-repetition-pulses to raise the <u>peak</u> to <u>average</u> power <u>ratio</u> sufficient to achieve the required I_{sp}.

- If long-life, high I_{sp} thrusters required high repetition-rate-pulsed electricity, a pulsed laser/photovoltaic receiver system might be configured to run pulsed thrusters directly with a minimum of power conditioning equipment.

- If high peak/average photovoltaic power is needed, we need more data on intrinsic (e.g., junction saturation effects) limits on the <u>peak</u> photovoltaic power/area.

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<u>Table 1</u>   Assumptions used for Manned Lunar Shuttle performance/cost calculations with different power/propulsion technologies (Table 3). Laser cases use a GBL with a GEO relay mirror, for vehicle illumination range = 3.8×10^5 km GEO to Low Lunar Orbit (LLO).

I. **Manned Lunar Shuttle Mission**

   (1) $M_{payload}$ = 12 tons, M_{shield} = 2.5 tons, 10 day one way trip time (M_{shield} = 1 ton for 2.5 day chemical-powered trip). 5 rem round trip dose.

   (2) 12 round trip missions per year, 3.8×10^5 km LEO to LLO.

   (3) One way Δv = 4.3 km/s (accel from LEO + decel to LLO).

   (4) Reusable shuttle vehicles cycling between LEO and LLO, with refueling in LLO via separate solar-powered cargo vehicles.

   (5) 250 $ lb LEO lift costs for propellant, 750 $ lb to LLO, for refueling 10 year amortization of capital items, full backup - one generating system, one on standby.

II. **Propulsion Technologies**

   (1) Chemical: I_{sp} = 290 sec for storable liquid fuel.

   (2) Nuclear/Solar Electric: α_e = 5 kg/kWe, plasma guns or ion propulsion, with I_{sp} optimized for lowest MLS system cost per year, η_{jet} = 0.37, η_e = 0.9.

   (3) Laser Ablation: Solid propellant replenished as cartridges, no skirt, but with foil laser concentrators. Specific impulse (optimized) scaled as
   $$I_{sp} = 700 \text{ sec } (\hat{\phi}_{focus}/4 \times 10^7 \text{ W/cm}^2)^{1/3}(\lambda/10\mu)^{2/3}$$
   η_{jet} = 0.2, Δt = 5.8×10^5 sec illumination (accel + decel time).

   (4) Laser Electric: Liquid metal or solid cartridge propellant in pulsed plasma guns, photocell receivers with α_e = 0.5 kg/kWe at λ = 0.8μ, maximum photocell power density 2 kWe/m^2 and mass density 1 kg/m^2. I_{sp} optimized for minimum system cost, η_{jet} = 0.37. η_e = 0.9, Δt = 5.8×10^5 sec illumination (accel + decel) time.

II. **Foil Concentrators (For Laser cases)**

   (1) mass/area = 10^{-2} kg/m^2 (4 micron Al foil, or equivalent).

   (2) Laser intensity concentration ratios (key parameter varied: 10^4 to 10^6 (D_{focus} = 10^{-2} to 10^{-3} $D_{concentrator}$) for laser

ablation cases, and 1 to 10 (D_{focus} = 1 to 0.3 $D_{concentrator}$)
for laser electric cases].

IV. GEO Relay Mirror (For Laser cases)
   (1) Diffraction-Limited Optics
      $D_t = 2.44 \lambda \, Z/D_c$,
      $Z = 3.8 \times 10^8$ m (GEO to LLO distance)
   (2) Mass = (100 kg/m^2) π $(D_t/2)^2$
   (3) Cost = (C_1) π $(D_t/2)^2 + C_2$
      C_1 = 2 M\$/m^2 for 10μ, 4 M\$/m^2 for 0.8μ
      C_2 = 10.5 M\$/ton x Mass (Tons)

V. Ground Base Telescope/Atmospheric Transmission
   (1) Average - attenuation through atmosphere
      2.5 x = properly tuned 10μ FEL
      5 x = 10.6μ CO_2 or 0.8μ FEL
   (2) Limit on peak laser intensity (ground)
      10^7 W/cm^2 - 10μ
      10^6 W/cm^2 - 0.8μ
   (3) Cost of ground base telescope
      = 2 M\$/m^2 x ($\pi \, D_{tel}^2/4$), for 10μ,
      4 M\$/m^2 for 0.8μ

VI. Cost of Lasers
   (1) $C_{laser} = \left(2 + \dfrac{X}{F_{rep}}\right)\left(\dfrac{\$}{watt}\right) \times \hat{P}_\nu(GBL)$

      where X = 500 for CO_2 + η_e = 0.10

      5000   FEL microwave
      10000 FEL 10μ $\Big\}$ η_e = 0.25 = P_ν (out)/P_e (in)
      20000 FEL 0.8μ

      F_{rep} = pulse repetition rate determined by $\hat{P}_\nu$ and $\check{P}_\nu$ requirements

VII. Cost of Gas Turbine Power
   (1) C = 500 \$/kWe x $\hat{P}_e$ (GBL) (Capital)
   (2) Annual fuel consumption for 12 missions:
      $C_{gas}/yr = \dfrac{\hat{P}_\nu \, (GBL)}{\eta_e \, \eta_{th}}$ F_{duty} 8760 $\dfrac{hr}{yr}$ x $\dfrac{0.016 \ \$}{10^3 \ W_e \cdot hr}$ $\approx$ 0.19 $\dfrac{M\$}{MW_e}$

Table 2 <u>Simple formulary used for Table 3</u>

Rocket Equation $Ln\ (M_i/M_f) = (\Delta v_{increment}/\bar{v}_{exhaust})$

M_I = initial MLS vehicle mass (kg)

M_f = final MLS vehicle mass (kg)

$\Delta v_{increment}$ = 4300 m/sec LEO to LLO, one way

$\bar{v}_{exhaust} = g_0\ I_{sp}$ (m/sec), I_{sp} in sec

Electrical power $\dot{P}_e = 1/2\ \dot{m}\left(\bar{v}_{exhaust}\right)^2 \eta_{jet}^{-1}\ \eta_e^{-1} \times 10^{-3} \dfrac{kWe}{We}$

where $\eta_{jet} = \dfrac{1/2\left(\bar{v}_{exhaust}\right)^2}{\displaystyle\int 1/2\ v^2\ f(v)dv} \dfrac{\langle v^2_{//}\rangle}{(\bar{v})^2} = 0.37$ for Laser-electric
Nuclear-electric
Solar-electric

$\eta_e = 0.9$

Propellant rate $\dot{m} = (M_i - M_f)/\Delta t$ (kg/sec)

Δt = FEL → MLS illumination (accel + decel) time = 6.7 days
     = 5.8×10^5 sec = 2/3 one-way trip time τ_{tr}

$M_f = M_{pay} + M_{shd} + M_{veh} + M_{pwr}$

Where M_{pay} = payload mass = 12 tons for cabin and life support
     systems for a crew of six.

M_{shd} = shield mass required to limit the round trip dose D

     $D = 9.6\ \tau_{tr}\ exp(-1.84\ M_{shd}) + 0.54\ \tau_{tr}\ exp(-0.11\ M_{shd}) \leq 5$ Rem
     → M_{shd} = 2.5 tons for optimum τ_{tr} = 10 days (laser, solar, nuclear
     or M_{shd} = 1.0 tons for τ_{tr} = 2.5 days (chemical case)

     M_{veh} = 0.1 M_I (mass of dry propellant tanks, vehicle
               frame and rocket motors).

     $M_{pwr} = \alpha_e\ \dot{P}_e$ (MLS), α_e = electrical supply specific mass
                         5 kg/kWe (solar/nuclear)
                         0.5 (photocell - 0.8μ laser)
                         0.0 (Chemical)

     $M_{pwr} \sim$ foil concentrator mass for laser-ablative cases.

Temporary crew shield for 10 hour (1hr)* Van Allenbelt crossings by the Manned Lunar Shuttle (MLS)

- Attenuation factor = 100 inside 10 kg/m^2 cabin shell
- Enclosure surface = 25 m^2
- Shield areal mass = 100 kg/m^2 (40kg/m^2)*
- Shield mass = 2.5 tons (1 ton)* for 5 rem round trip dose
- Values for faster chemical powered MLS
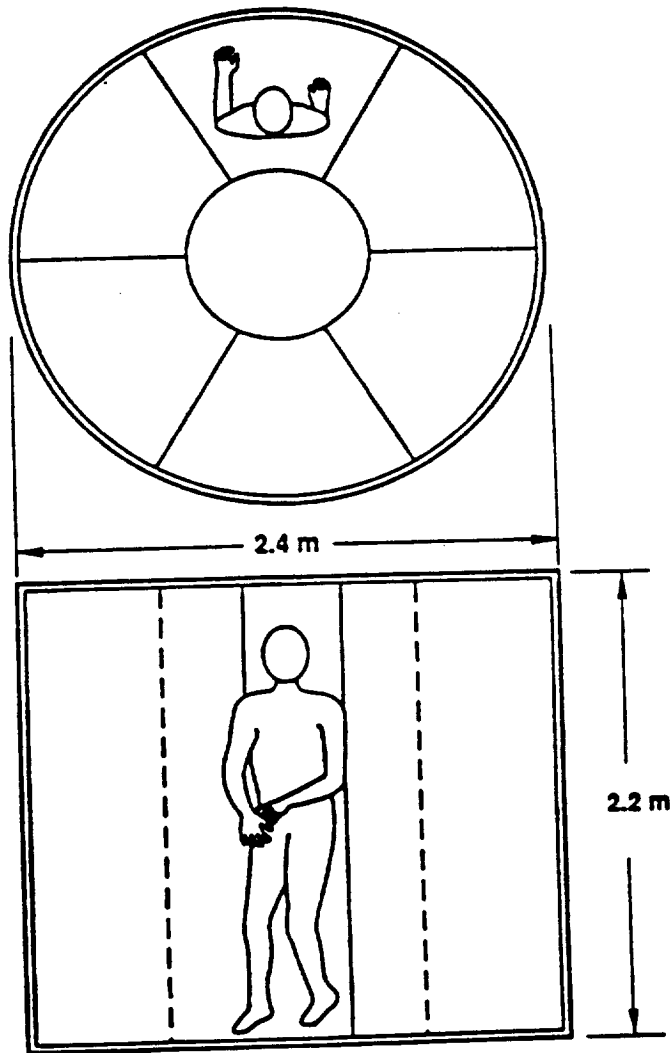
2.4 m

2.2 m

$\Delta v_{inc} \approx 4.3$ km/s
$\alpha_e \approx 0.5$ kg/kWe (0.8 μ photocells)
$M_{pay} \approx 12$ tons (crew of 6)
Round trip dose $\approx$ 5 rem
Twelve round trips per year
Propellant Cost ≈ 2000 $/lb to LEO
4 MLS systems operating parallel
2 MLS systems operating parallel

Crew shield mass M_{shd} (tons) →

Avg laser-converted power to MLS motor P_e (MLS) MW$_e$ →

Annual MLS system expenditure/yr (10^9/yr) → C_{MLS}

C_{MLS}

M_{shd}

P_e (MLS)

Optimum specific impulse

I_{sp} (1500 s)

I_{sp} (2000 s)

$\left(\dfrac{I_{sp}}{2500\,s}\right)$

$\left(\dfrac{I_{sp}}{3000\,s}\right)$

$\left(\dfrac{I_{sp}}{3000\,s}\right)$

τ_{tr} one way trip time (LEO → LLO) (days)

Table 3 Characteristic parameters and costs for Manned Lunar Shuttle (MLS) systems powered by different power/propulsion technologies, under assumptions given in Tables 1 and 2

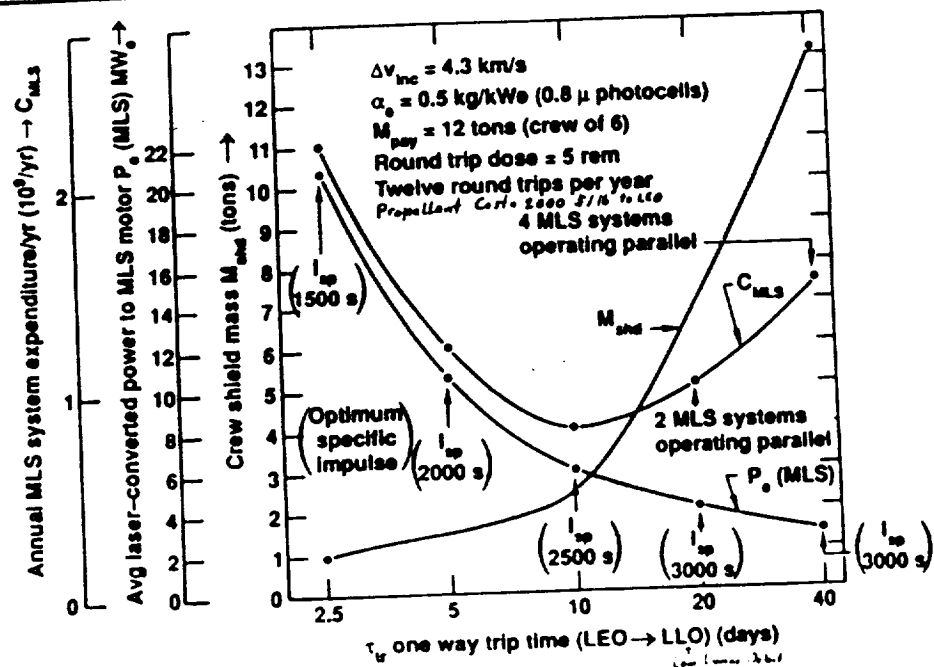| Parameter	Conv. Chemical	Nuclear/ Solar Electric $\alpha_e = 5$	10μ Laser Ablation $D_f = 10^{-2}D_c$	10μ Laser Ablation $D_f = 10^{-3}D_c$	0.8μ Laser Ablation $D_f = 10^{-2}D_c$	0/8μ Laser Electric $\alpha_e = 0.5$ $D_f = 0.3 D_c$	0.8μ Laser Electric $\alpha_e = 0.5$ $D_f = D_c$
Specific Impulse I_{sp} (s) (Optimized)	290	800	700	700**	700	2500	2500
MLS initial mass M_i (tons)	101	102	34	41	34	23.5	23.5
MLS final mass M_f (tons)	23	60	18	22	18	19.8	19.8
MLS propellant use each way (tons)	78	42	15	19	16	3.7	3.7
MLS laser/electric power MW (ν) or MW(e)	NA	7.0 (e)	3.1 (ν)	3.9 (ν)	3.2 (ν)	9.0 (ν) 6.0 (e)	9.0 (ν) 6.0 (e)
MLS focus dia. (m)	NA	NA	2.32	0.662	0.74	62	62
MLS collector dia. (m)	NA	NA	232	662	74	200	62
GEO relay mirror dia. (m)	NA	NA	40	14	10	3.7	11.9
Uplink Telescope mirror dia. (m)	NA	NA	7.3 [10]*	2.1	25	2.4	2.4
GBL output (MW_ν)	NA	NA	7.8 [15.6]	9.8	15.8	45	45
GBL power (MW_e)	NA	NA	31 [156]	39	63	180	180
GBL energy/pulse (kJ)	NA	NA	212 [8460]	17.2	238	2.25	2.25
GBL rep rate F_{rep} (Hz)	NA	NA	37 [1.8]	566	66	20,000	20,000
Annual Propellant (M$/yr)	2060	1120	408	507	411	98	98
10% of MLS vehicles capital (M$/yr)	48	127	39	46	38	42	42
10% of optics capital M$/yr	NA	NA	784 [800]	95	460	14	1:6
10% of laser capital (M$/yr)	NA	NA	428 [854]	38	960	27	27
GBL gas turbine 10% capital and fuel (M$/yr)	NA	NA	9 [46]	11	18	52	52
Total MLS system cost (M$/yr)	2108	1247	1668 [2147]	697	1887	233	335

* Quantities in brackets assume a conventional CO_2 gas laser with 2 x more atmospheric attenuation than with tuned FEL.
** Not optimized; optimum I_{sp} would be slightly higher, with higher $\hat{\phi}_{laser}$.

Appendix B. An Alternate Strategy for Low Specific Power Reactors Powering Interplanetary Spacecraft, Based on Exploiting Lasers and Lunar Resources

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INTRODUCTION

A key requirement setting the minimum electric propulsion performance (specific power a_e = kWe/kg) for manned Mars missions is the maximum allowable radiation dose to the crew during the long transits between Earth and Mars. Penetrating galactic cosmic rays and secondary neutron showers give about 0.1 rem/day dose rate, which only massive shielding (e.g. a meter of concrete) can reduce significantly. With a humane allowance for cabin space, the shielding mass could be large enough to prohibitively escalate the propellant consumption required for reasonable trip times.

One solution that has been proposed is the use of permanently-cycling spaceships with transfer vehicles, which avoid acceleration and deceleration of large shielding mass, but which constrain round trip periods to long 4 year cycles. A more desirable alternative is to develop sufficient propulsion system performance for sufficiently short trip times that maximum dose limits not be exceeded. Such dose limits are not yet promulgated for space travel, but for reference, the US limits routine doses to nuclear plant workers to 5 rem/year, and 25 rem for one-time accident exposures. Taking the latter for astronauts, the round trip time must be less than 250 days (0.7 year), at a dose rate of 0.1 rem/day. Then, for the Mars mission requirements discussed in Section 4, the minimum specific power for less than 1000 ton initial mass and 0.7 round trip travel time is found from Fig. A1 to be 0.33 kWe/kg. Corresponding total mission delta "V", specific impulse/power, and propellant consumption are indicated in Fig. A2, A3, and A4, respectively. Dose limits lower than 25 rem would require higher specific power capability than 0.33 kWe/kg.

Given the present state of knowledge about solar, fission, and fusion candidates for spacecraft power, we cannot say that such minimum specific power values can be assured with any candidate, although, with various degrees of optimism, we might say that such a performance level might be reached with advances in technology. Rather than have the fate of important Mars and other manned interplanetary missions depend solely on the achievement of such threshold specific powers, it would be prudent to seek other paths to achieve such missions, even if fission or fusion reactor developments turn out with lower specific power than 0.33 kWe/kg. One such concept, which I dub "LASERPATH", would site lower specific power reactors at a lunar base, and use their electricity to power large free-electron-lasers, which in turn remotely power lower mass spacecraft at much higher specific powers. Given that reactors at 0.33 kWe/kg were indeed available, it could still be more advantageous to base them on the moon for laser-powering the vehicles instead of directly powering them on-board with the same reactor specific power, provided that (a), the laser conversion efficiency were sufficiently high at sufficiently short wavelengths, (b), the specific power of laser-driven photovoltaics (for the vehicle electrical power) were sufficiently greater than 0.33 kWe/kg, and (c), a large fraction of the lunar-based reactors and lasers could be constructed from indigenous lunar materials. The following description of the LASERPATH concept, and comparisons of LASERPATH powered cases with on-board reactor-powered cases,

are not an attempt to fully substantiate these ideas, but possibilities that warrant further study.

LUNAR-BASED FREE ELECTRON LASERS AND TRANSMITTERS

There have been several previous assessments of laser space power transmission,[1,2] but since these studies were completed, the recent advent of free-electron-lasers (FEL) in the US SDI program and in the Japanese Center for Science and Technology Development at Osaka appear much more promising to meet the desired characteristics for lunar-based laser power transmission: 100 megawatt-level high average power, high conversion efficiency (20 to 40%), high specific power ($\geq$1 kWe/kg), and tunability to any desired wavelength. The last characteristic is important to match hv to the optimum quantum energy above the bandgap of the vehicle photovoltaic receiver, to achieve high photovoltaic power density and conversion efficiency described in the next section.

Figure 5 illustrates the basic components of one type of FEL, called Induction-Linac FEL, or IFEL, which is under development at the Lawrence Livermore National Laboratory. 40% conversion efficiency at peak powers of a gigawatt have been recently demonstrated in a microwave IFEL at LLNL, and experiments at much shorter wavelengths are under way. Another basic type of FEL driven by an RF Linac is under development at Los Alamos National Laboratory (and also in Japan). Both approaches accelerate an electron beam to high energies, and pass the beam through a series of alternating transverse magnetic fields, called a wiggler, as shown in Fig. 5. Provided a certain relationship between the electron energy, input light wavelength, wiggler field, and wiggler wavelength are satisfied, the periodic transverse motion of the electron beam in the wiggler field amplifies the input light intensity. Because the gain medium in the FEL is simply a bunch of free electrons traveling in a vacuum magnetic field, and because there need be no window in space vacuum between the wiggler and reflective (Cassegrain-type) transmitter optics, there is no fundamental limit on the laser intensity set by the breakdown of materials, nor any constraints on the wavelength set by any atomic optical transitions. Thus, in principle, the power density in an FEL can be quite high, and the wavelength adjusted to any desired value.

Instead of being limited by the gain medium, the maximum IFEL power density would be set by cooling of the dielectric and ferromagnetic materials used in the magnetic pulse sources and accelerator modules of Fig. 5. Storing typical energy densities (in a single pulse) of a hundred joules per kilogram, the "intrinsic" IFEL specific power in these accelerators active media

$$a_{IFEL} \text{ (intrinsic)} \approx 0.1 \text{ kJ/kg} \times F_{rep}(Hz)$$

depends on the pulse repetition rate F_{rep}. With solid state switching, the upper limit on F_{rep} set by cooling is currently expected to be 10 to 20 kilohertz. Thus, intrinsic $a_{IFEL} > 10^3$ kWe/kg are possible. Of course, the overall IFEL system specific power will be much lower due to structure, wigglers, power supplies and space radiators for cooling. Thus, the maximum system a_{IFEL} might not be much larger than 1 kWe/kg. At this specific power, the laser system mass will be dominated by the structure, power supplies, and radiators.

LUNAR-BASED TRANSMITTER

The transmitter to direct the laser beam out of the FEL to the spacecraft photovoltaic receiver millions of kilometers away needs to be very large, both to limit diffraction losses discussed later on, and to allow adequate cooling at the high beam power levels envisioned. To achieve diffraction-limited beam quality, the favored approach is to subdivide a large aperture transmitter into many smaller mirror segments. Each segment would be a thin, hexagonal wafer supported and adjusted by a set of three small, computer-controlled electromagnetic or piezoelectric actuators. In this way, arbitrarily-large phased optical transmitter arrays could be constructed at a moderate areal mass of about 40 kg/m^2. Balancing beam losses (using optical coatings) with radiative cooling would limit average beam intensity to about 100 kW/m^2. This corresponds to a transmitter specific power of 2.5 kW(beam)/kg, 10% as much mass as the IFEL at 1 kWe/kg and 25% efficiency.

The adaptive optics would control the beam phase front to within a small fraction of a laser wavelength, correct for thermal and gravitational distortions, and provide a small angular range of electronic beam steering. The beam would most likely be directed to a relay mirror (also adaptive) at a high synchronous lunar orbit, and then redirected to track the spacecraft. The spacecraft receiver would best be a large diameter, parabolic foil collector ($\leq 10^{-2}$ kg/m^2 areal mass, $D_r \sim 1000$ m diameter), which concentrates the laser beam onto a smaller ($D_f \sim 100$ m) photovoltaic array at much higher areal mass (≤ 1 kg/m^2). The characteristics of this photovoltaic array is discussed next, and then the allowed laser transmission range versus laser power will be estimated.

PHOTOVOLTAIC RECEIVER CHARACTERISTICS

It is well known that photovoltaic conversion efficiencies with spectrally-narrow laser light can be much higher than with solar radiation, much of the latter spectrum falling uselessly outside the semiconductor band gap.[3] A promising photovoltaic candidate for a Mars LASERPATH mission is thin diamond-film semiconductor, now under development at several laboratories. With a 5 eV band gap energy E_b, a high conversion efficiency (e.g. 70%) might be achieved with UV laser wavelengths of 100 to 200 nm.[4] Furthermore, the conversion efficiency, should remain high up to higher temperatures, allowing more waste heat radiation off the wafer backsides.

For 100 μ-thick thin film photovoltaic array at 1 kg/m^2 areal mass (including structure), and an equal total foil collector mass, a specific power of 10 kWe/kg would require 30 kW/m^2 average laser intensity on the photovoltaics (300 W/m^2 on the foil collector), to produce 20 kWe/m^2 of photovoltaic area. The waste heat radiated would be 10 kW_{th}/m^2 off the back side, giving an equilibrium photovoltaic temperature of 670°K.

An important consideration for manned missions is reliability, with backups to system failure, if possible. With 4 month one way trip times, failure of the lunar base reactor or laser may permit time to repair (if the failure occurs midcourse), using the lunar base infrastructure, or even shipping up spare parts from Earth. Building-in redundancy (an extra reactor and laser, for example) also helps. But ultimately, if all else fails, a LASERPATH system has an emergency backup energy source, albeit with less usable power: the sun. In principle, the large foil collectors envisioned could also deliver solar radiation to the photovoltaics, up to the limit imposed by photovoltaic

temperature limits and waste heat radiation. For diamond photocells, the bandgap accepts only a slice of the less intense solar UV spectrum, so the solar conversion efficiency would probably be low, perhaps only a couple of percent. Nonetheless, since the concentrated solar flux and operating temperature can be higher, the diamond photovoltaic array might still have solar output of electricity comparable to conventional silicon solar cells ($\sim$0.2 kWe/m^2). With emergency solar power, a LASERPATH vehicle could limp home, provided it was not nearly out of propellant when the laser failure occurred. The astronauts may get a higher dose with a longer solar-powered trip home, but they would still survive.

RANGE OF LASER-POWER TRANSMISSION

Now that we have determined laser intensities at the lunar-base transmitter (100 kW/m^2), and on the photovoltaic array (30 kW/m^2 within D_f, the collector focus), we can determine a relationship between average laser power P_L and range R between transmitter and the foil receiver (collector), provided we specify the ratio of foil receiver diameter to photovoltaic (focus) diameter, D_r/D_f:

$$D_r = (D_r/D_f) \; D_f = (D_r/D_f) \; [(4/\pi)(0.9 \; P_L(W))/(3 \times 10^4(W/m^2))]^{1/2} \qquad (1)$$

$$D_t = [(4/\pi)(P_L(W))/(10^5(W/m^2))]^{1/2} \qquad (2)$$

Now, diffraction relates the product $D_r D_t$ to the range R and the laser wavelength l according to

$$D_r D_t = 2.44 \; R \; l = 220 \; P_L(MW) , \qquad (3)$$

where we have used Eq. 1 and 2. The results are plotted in Fig. 6 for various wavelengths l. We see from Fig. 6 that, for the short UV wavelengths we assume, a Mars LASERPATH mission can be achieved with 200 MW laser power. Longer wavelength lasers require either more power, or several laser stations enroute, to decrease the range requirement. Eventually, for regular manned shuttles supporting a permanent base, it would be advantageous to install at least one additional reactor and UV laser on the Martian moon Phobos.

From the mission requirements plotted in Fig. A3, we see that a 0.7 year round trip travel time (25 rem dose) requires 129 MWe for a 10 kWe/kg specific power. With a 90% foil collection efficiency and a 70% conversion efficiency, the required laser beam power is 129/[(0.9)(0.7)] $\sim$200 MW. Thus, there is a good match between the mission requirements and the LASERPATH power system performance.

LUNAR REACTOR MASS

Finally, we can address the performance requirements for lunar-based reactors (or other power sources) to power the Mars LASERPATH mission. Such lunar-based power sources could in principle be fission or fusion reactors, or even large solar-power stations, as envisioned in Peter Glaser's solar power satellite proposal. In any case, we inquire whether or not the propellant and vehicle mass savings made possible by laser driven photovoltaics could offset the greater reactor or power source

mass incurred by the inefficiency of laser conversion in the LASERPATH scheme. Taking our IFEL laser example with a conversion efficiency of 25%, the 200 MW laser power output demands an 800 MWe lunar-based power source, ten times the 80 MWe required for an on-board power source with the 0.33 kWe/kg specific power necessary to meet the same 0.7 year round trip mission (see Fig. A3). If one assumes the vehicles are reusable (but keep an extra spare vehicle), one could compare the sum of the vehicles' power/propulsion system mass and the total propellant consumed for say, 10 round trips (20 years, given the 2 year Earth Mars Synodic period), with the corresponding sum in the LASERPATH case plus the added mass of the laser (M_{laser} = 800 MWe/(0.9 kWe/kg) metric tons, including the transmitter optics, laser power conditioning, cooling, and supports) and the added mass of the reactor ($M_{reactor}$ = 800 MWe/a_r). Such comparisons are presented in Table 1, for two on-board power sources characterized by a_r =0.33 kWe/kg (the minimum required for the mission - case 1), and a_r = 1 kWe/kg (case 2), to represent the aspiration of more advanced fusion-powered vehicles, to be compared with two LASERPATH examples (cases 3 and 4) characterized by lunar-reactor specific powers of 0.33 kWe/kg and 0.067 kWe/kg, respectively. As the specific detail of optimized lunar reactor designs is beyond the scope of this work, I seek to characterize such reactors by specifying only their specific power. The lunar reactor case 3 with 0.33 kWe/kg is chosen to compare with case 1, having the same specific power for an on-board reactor which can barely meet the mission requirement. The lunar reactor case 4 with 0.067 kWe/kg is chosen to illustrate what happens with a specific power no better than SP-100 nuclear units, which cannot meet the Mars mission as on-board reactors (at lest, with <25 rem round-trip dose constraints).

LUNAR MASS UTILIZATION

Normally, one compares total mass between competing space power systems meeting the same mission, since transportation costs to LEO could likely dominate over terrestrial material and fabrication costs for >10^3 ton space systems. When that is the case, the unit costs of very different materials and fabrications tend to be closer to the same transportation costs per unit mass. This is even more likely to be the case for lunar space systems, if transport from the Earth to the Moon were required.

Now, the NASA office of exploration is sponsoring studies of possible use of lunar materials for space development, and ways to manufacture various commodities and structures on the moon. For example, heavy radiation shielding might be made of lunar concrete, iron-nickel micrometeorite particles collected from lunar soil might provide steel structures, and traces of low-atomic-number solar-wind gases trapped in the finer lunar dust can be outgassed by heating (H_2, H_2O, He, CO_2, etc). Without a detailed design, one can't determine what fraction f_m of a given lunar system, such as a reactor, could be made of indigenous lunar materials. However, if a substantial fraction of reactor systems, (which might be dominated by structures, shielding, transformer iron in power supplies, etc.) could be made of lunar material, and furthermore, if such a fraction were different for different types of reactors, (as is likely to be the case), then the important comparison between competing propulsion systems would be the total mass minus any lunar-origin mass, i.e., the mass portion that must be transported from Earth. This assumes that the unit cost of Earth-origin mass much exceeds the unit cost of lunar-origin mass, which would be the case if the total lunar mass of each type produced were a large multiple of the initial investment of lunar mining and

manufacturing equipment mass. If the lunar production equipment mass were not negligible, it could be included as an effectively smaller lunar mass utilization factor f_m.

I will not attempt to fully justify the f_m values assumed in Table I, which are picked primarily to illustrate how the impact of large f_m fractions might change the comparative system economics of the various cases. I inserted just a tiny bit of logic to the f_m assumptions: for the f_m values pertaining to power generation and conversion (reactors and lasers), I suppose that f_m can in general increase with decreasing specific power, on the argument that, the higher the specific power, the narrower the choice of materials which can reach the higher performance levels, and the more likely such specialty materials would have to be transported from Earth. Thus, I chose $f_m = 0.02$ for $a = 10$, 0.18 for $a = 1$, 0.45 for $a = 0.33$, and 0.95 for $a = 0.067$, for either reactors or lasers, which reflects this tendency, although the actual values are arbitrary. I would like to mention, at least in the case of magnetic fusion of which I am most familiar, that $f_m = 0.95$ is not obviously impossible to achieve. At 800 MWe and $a_r = 0.067$, a 12000 ton D-3He tokamak (5) might consist of 4000 tons superconducting magnets (consisting of 3400 tons of iron-nickel steel structure, 300 tons of aluminum stabilizer, and 300 tons of superconducting wire), 3000 tons of steel neutron shielding, 2000 tons of blankets (which could be a simple, helium cooled, ferritic steel structure), 2700 tons of heat injection space radiators (mainly low-pressure steel tubing), and 300 tons of solid-state microwave rectenna convertors. If meteorite-derived steel can be used, there would be essentially only 600 tons of superconductor and rectenna convertors to import from Earth.

As for the vehicle propellant, I assumed two different values for $f_{mp} = 0$ and 0.7, to illustrate the impact of using imported propellant ($f_{mp} = 0$), such as argon or sodium, or using lunar-derived propellant, such as hydrogen. Most electric-powered plasma thrusters would run on either heavy noble gases, alkali metals, mercury, or cesium, none of which are likely to be lunar indigenous, due to their intrinsic volatility. Although hydrogen is difficult to use in electric thrusters, and difficult to store for long periods, these problems might be overcome in the future. The hydrogen exists only in trace amounts in lunar soil, so f_{mp} should not be too close to unity when accounting for the hydrogen extraction, liquefaction, and storage equipment mass.

CONCLUSIONS

From the results in Table 1 we can draw some conclusions (some more qualitative than quantitative, until more analysis is done).

(1)   The rationale for LASERPATH hinges mainly on how high a specific power fission, fusion, or solar power systems can be developed for powering manned vehicles: if, for example, sufficiently advanced fusion reactors could achieve $a_r = 1$ kWe/kg, then it would be best to pursue the conventional approach, with the reactor carried on-board. If, however, $a_r = 0.33$ kWe/kg, then a mission with less than 0.7 year travel time and 25 rem doses cannot be achieved at all with on-board reactors, and in this case the LASERPATH approach might meet the mission requirement with lower specific mass reactors, and with comparable total mass investment as if $a_r = 0.33$ kWe/kg reactors were available.

photovoltaics, adaptive transmitter optics, and efficient free-electron-lasers, all of which appear to be promising, but remain to be demonstrated at the performance levels needed. NASA should encourage and participate in such developments, as a hedge against the uncertainty of reactors reaching the high specific powers required for on-board power systems.

(3)   The actual commitment of mass transport from Earth to establish lunar power reactors and lasers might be heavily influenced by the availability and suitability of lunar materials in their construction. NASA should sponsor a study, in conjunction with the ongoing lunar resource studies, to explore the different degrees to which different lunar power sources--fission, fusion, and solar--can utilize lunar materials, and in doing so, encourage innovative thinking from reactor designers to more fully exploit lunar materials, i.e., reoptimize the reactor designs for the lunar base development.

(4)   As the duty factor required for Mars missions every two years is low (~35%), investment in a lunar LASERPATH system could be utilized for a variety of other space enterprises in between shots, further leveraging the investment.

Table 1. Case Comparisons of Propulsion System Mass: On-Board Reactors versus Lunar-Based Reactors + Laser Transmission.

Parameter	Case 1 On-Board Reactor 0.33 kWe/kg	Case 2 On-Board Reactor 1 kWe/kg	Case 3 Lunar-Based Reactor 0.33 kWe/kg	Case 4 Lunar-Based Reactor 0.067 kWe/kg
Manned Mars Vehicle Power, Specific Power	80 MWe 0.33 kWe/kg	115 MWe 1 kWe/kg	129 MWe[a] 10 kWe/kg	129 MWe 10 kWe/kg
Two-Vehicle Power System Mass (MT)	480 (264)[b]	115(94)	26(25)	26(25)
Propellant (MT) for 10 round trips	6300[1890][c]	908[272]	160[48]	160[48]
Lunar-based Reactor Mass (MT)	NA	NA	2400(1320)	12000(600)
Lunar-Base Laser + Transmitter Mass (MT)	NA	NA	800(722)	880(722)
Total Pwr/Prop/Sys[d] Mass (MT)	6780	1023	3466	13,066
Total Pwr/Prop/Sys Mass (MT), Non-Lunar Origin, if f_{mp} = 0	(6564)	(1002)	(2227)	(1507)
Total Pwr/Prop/Sys Mass (MT), Non-Lunar Origin, if f_{mp} = 0.7	[2154]	[366]	[2115]	[1395]

Assumptions: 133 ton payload, 250 day round-trip travel time, (25 rem round trip dose), 2 vehicles (one for standby), specific power of lunar-based laser + optics system = 0.9 kWe/kg lunar-mass-utilization factors f_m: 0.02 for a = 10, 0.18 for a = 1, 0.45 for a = 0.33, 0.95 for a = 0.067; propellant f_{mp} = 0 or 0.7 (as indicated).

[a]Foil concentrators + photovoltaic array for vehicle power (case 3 and 4)
[b]Figures in parenthesis subtract mass of lunar origin $(1 - f_m)M$.
[c]Figures in bracket adjusted by $(1 - f_m)$ = 0.3 factor for propellant.
[d]Includes vehicle power systems for 2 vehicles, propellant for 10 trips, and lunar-based reactors and lasers, where appropriate.

REFERENCES

(1) R.D. Arno, J.S. MacKay, and K. Nishioka "Applications Analysis of High Energy Lasers" NASA AMES report NASA TM X-62, 142 March 1972.

(2) W.J. Schafer Associates, Inc., "A Study to Survey NASA Laser Applications" Feb. 1978, in "Space Laser Transmission STudies," by M.D. Williams and E.J. Conway, editors, NASA Conference Publication 2214, (1982).

(3) G.H. Walker and J.H. Heinbockel, "Photovoltaic Conversions of Laser Power to Electrical Power," NASA Langley report NASA TM 89041 (Sept. 1988).

(4) B.G. Logan "Initiative for the 21st Century: Advanced Space Power and Propulsion Based on Lasers," Seminar given at NASA Lewis Research Center, April 26, 1988. Lawrence Livermore National Laboratory, Report UCRL-98520 (preprint).

(5) G.L. Kulcinski, G.A. Emmert, J.P. Blanchard, L. El-Guebaly, H.Y. Khater, J.F. Santarius, M.E. Sawan, I.N. Sviatoslavsky, L.J. Wittenberg, and R.J. Witt, "Apollo-An Advanced Fuel Fusion Power Reactor for the 21st Century," University of Wisconsin Fusion Technology Institute, Report UWFDM-780, Oct. 1988.

BEAMED LASER PROPULSION

PRESENTATION TO

TECHNOLOGY WORKSHOP ON LASER BEAMED POWER


FEBRUARY 5, 1991

NASA LERC

DAVE BYERS
MIKE LAPOINTE

BEAMED LASER PROPULSION

OUTLINE

- IN-SPACE PROPULSION IMPACTS

- BEAMED LASER PROPULSION CONCEPTS

- LERC TECHNOLOGY STATUS

  - ELECTRIC PROPULSION

  - BEAMED LASER PROPULSION

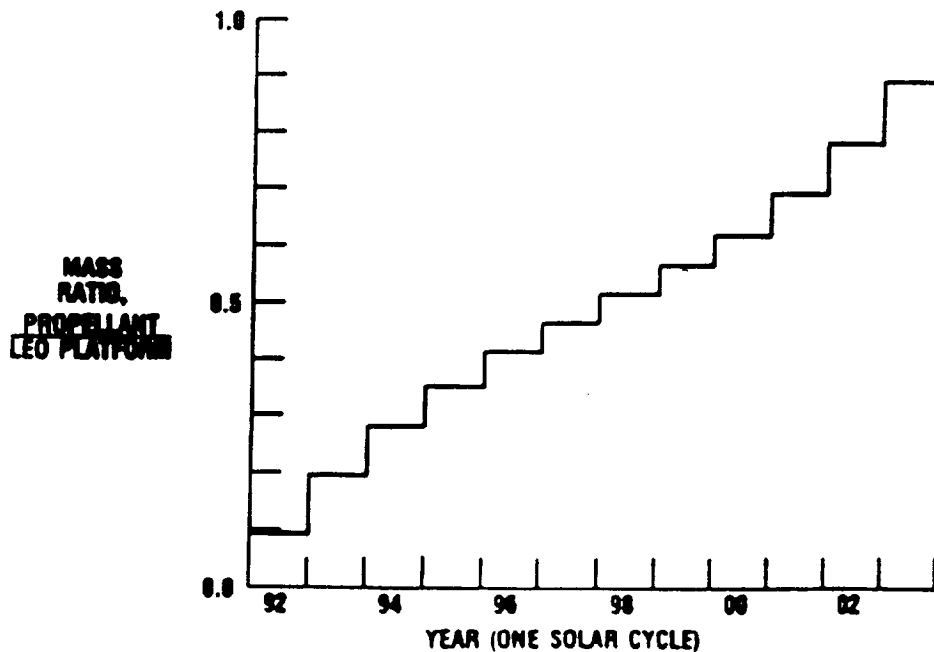   = PHASE CONJUGATED/"NONDIFFRACTING" WAVES

    = LASER ROCKET

- SUMMARY

LOW THRUST PRIMARY AND AUXILIARY PROPULSION
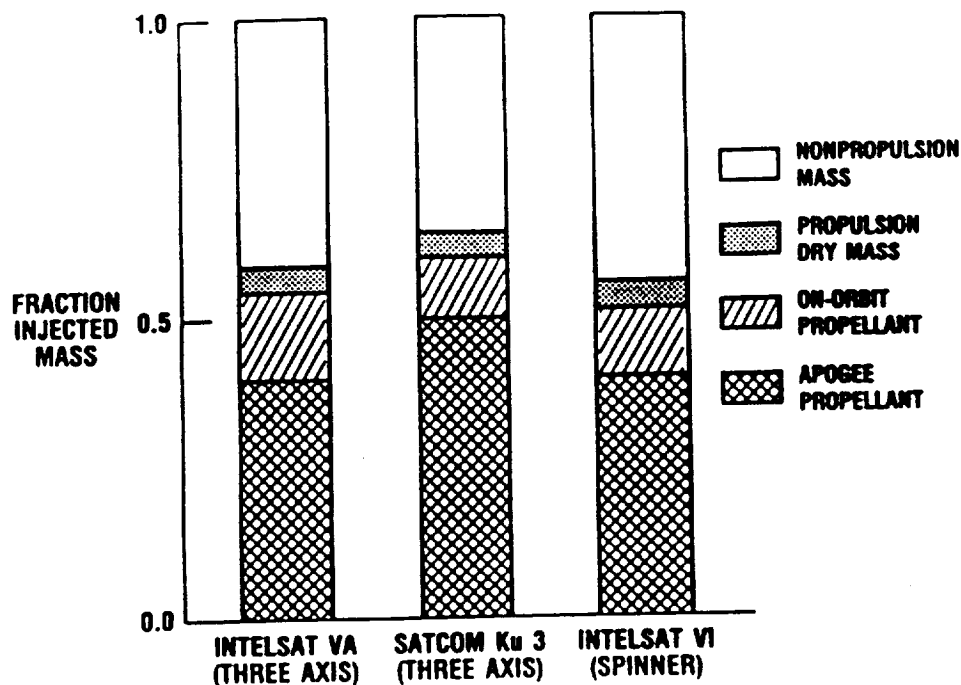### INTEGRATED H/O SYSTEMS

APS OFFERS MAJOR LEVERAGE

SHUTTLE
ORBITER
APS MASS
– KLBS

DUE EAST   SORTIE

MISSION
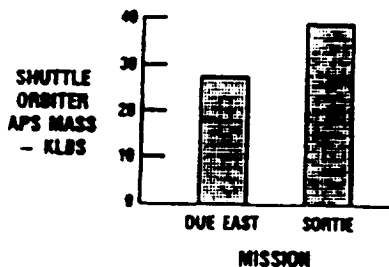
• APS MASS IS 11.4% TO 18.5% OF ORBITER

RATIOS OF CUMULATIVE DRAG-MAKEUP AND REBOOST
PROPELLANT MASS TO LEO PLATFORM (ISF) MASS
(WATER RESISTOJET, I_{SP} OF 152 S)

MASS
RATIO,
PROPELLANT
LEO PLATFORM

YEAR (ONE SOLAR CYCLE)

GEOSYNCHRONOUS TRANSFER ORBIT MASS FRACTIONS FOR RECENT COMMUNICATIONS SATELLITES

FRACTION INJECTED MASS

- NONPROPULSION MASS
- PROPULSION DRY MASS
- ON-ORBIT PROPELLANT
- APOGEE PROPELLANT

INTELSAT VA (THREE AXIS) SATCOM Ku 3 (THREE AXIS) INTELSAT VI (SPINNER)

CD-89-40283

GEO ORBIT TRANSFER MASS DISTRIBUTION[1]

LEO MASS, %

- PAYLOAD
- SECOND STAGE
- FIRST STAGE
- PROPELLANT
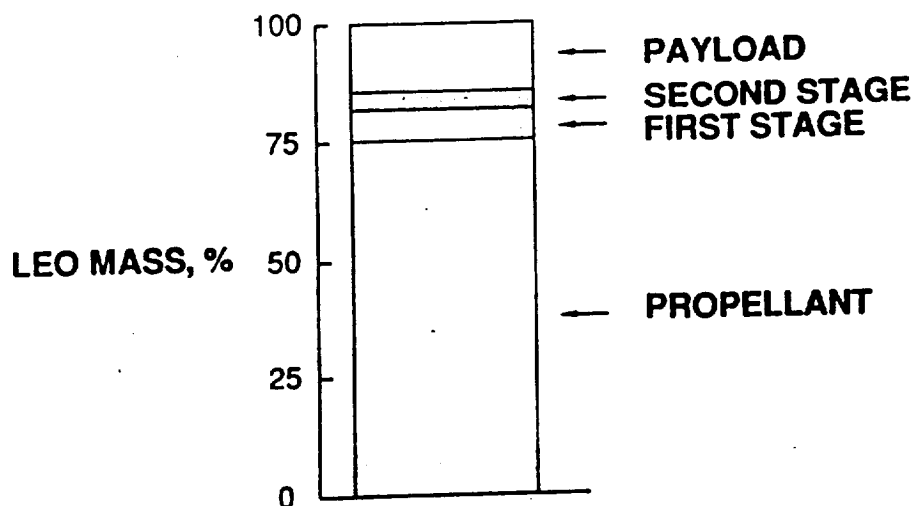
GEO PAYLOADS SMALL FRACTION OF LEO MASS

(1) 5250 LBS BOL/GEO PAYLOAD, TITAN IV/IUS
FROM AIAA 89-2496 "Electric Orbital Transfer Vehicle - A Military Perspective", S Rosen and J.Sloan AFSD.

II-3

PLANETARY SPACECRAFT INJECTED MASS FRACTIONS

CO-87-40282
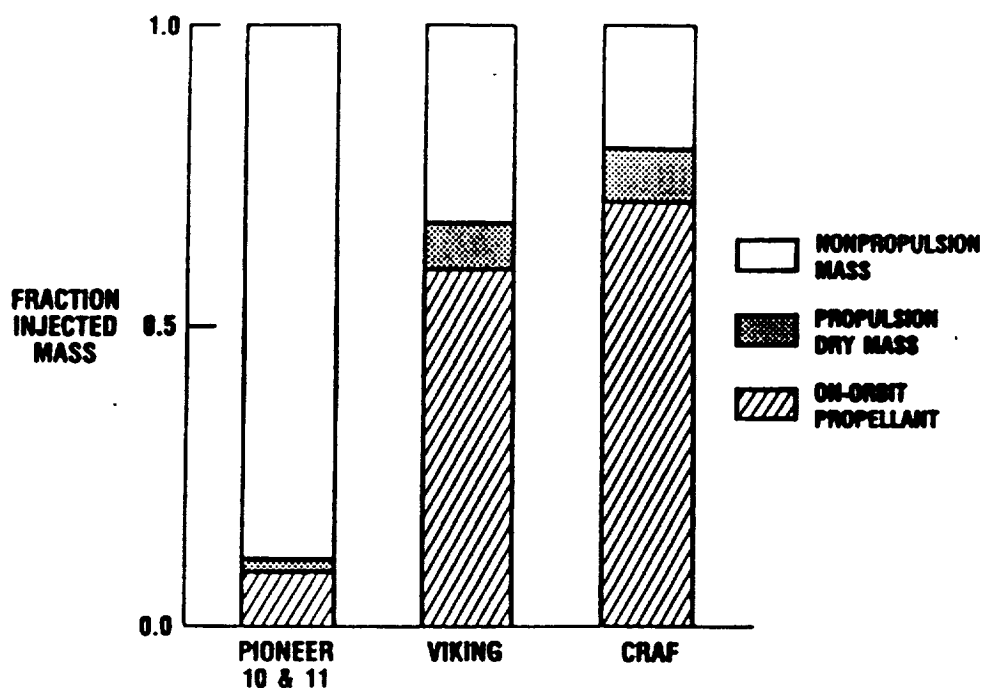
SPACE PROPULSION TECHNOLOGY DIVISION — NASA Lewis Research Center

SOA IN-SPACE PROPULSION IMPACTS

- 11 TO 19% OF SHUTTLE ORBITER MASS

- MAJOR LEO PLATFORM RESUPPPLY PENALTY

- 55-65% OF GTO INJECTED MASS

- OVER 80% OF PLANETARY INJECTED MASS

- ETO & STV PAYLOADS OFTEN DOMINATED BY IN-SPACE PROPULSION

- FRACTIONAL PENALTIES OF IN-SPACE PROPULSION REQUIRE INCREASED PERFORMANCE

II-4

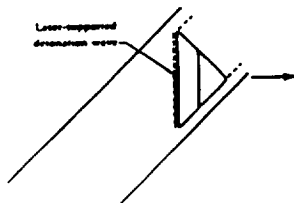## BEAMED LASER PROPULSION CONCEPTS

LASER BASING

- GROUND

- SPACE

PROPULSION

- DIRECT

  - HYDROGEN ROCKET

  - LASER SUSTAINED DETONATION

- LASER TO ELECTRIC

BEAMED LASER PROPULSION CONCEPTS

	LASER SUSTAINED DETONATION	H_2 ROCKET	LASER TO ELECTRIC
Isp (S)	500 - 800 (?)	500 - 1500 (?)	1400 - 10,000
MODE	RP	CW	CW
APPLICATIONS	LAUNCH LEO AUXILIARY	EARTH ORBIT - OTV - AUXILIARY	EARTH & PLANETARY ORBIT - OTV - AUXILIARY
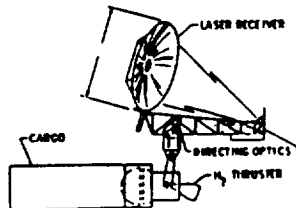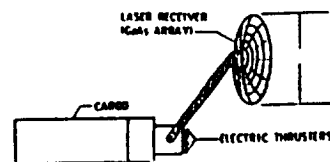
H-5

BEAMED LASER PROPULSION

OBSERVATIONS

- **CONTINUOUS LASER POWER NOT ESSENTIAL**

    - **IMPULSIVE PROPULSION EFFECTIVE & SOMETIMES OPTIMAL**

    - **POWER STORAGE NOT REQUIRED**

- **MANY STUDIES INDICATE BENEFITS OF <u>BOTH</u> EARTH & SPACE BASED BEAMED LASER PROPULSION**

- **GERMANE/ON-GOING LERC R&T**

    - **ELECTRIC PROPULSION**
    - **CONJUGATE/"NONDIFFRACTING" WAVES**
    - **H_2 ROCKET (SUPPORTED BY SDIO)**

ELECTRIC PROPULSION

- **CONCEPTS**

- **SUMMARY STATUS**

THREE CLASSES OF CONCEPTS

ELECTROTHERMAL

- GAS-HEATED BY RESISTORS AND/OR ARCS AND EXPANDED THROUGH A NOZZLE
  - RESISTOJETS
  - ARCJETS
  - PULSED

ELECTROSTATIC

- IONS ELECTROSTA- TICALLY ACCELERATED
  - ION

ELECTROMAGNETIC

- PLASMAS ACCELERATED BY ELECTRIC AND MAGNETIC FIELDS
  - MPD
  - PULSED PLASMA

ELECTRIC PROPULSION

STATUS

77 SPACE TESTS CONDUCTED

TYPE		ORIGIN	
ELECROTHERMAL	33	CHINA	1
ELECTROSTATIC	16	JAPAN	7
ELECTROMAGNETIC	28	USSR	21
		USA	48
	77		77

(1) SCHREIB, R., AIAA PAPER NO. 88-0777, MARCH 1988

CD-90-47534

ELECTRIC PROPULSION

STATUS

LOW POWER (ORBIT ADJUST) SYSTEMS OPERATIONAL/BASELINED

- NOVA
  - PULSED PLASMA

- SPACE STATION
  - RESISTOJETS

- US & FOREIGN COMSATS
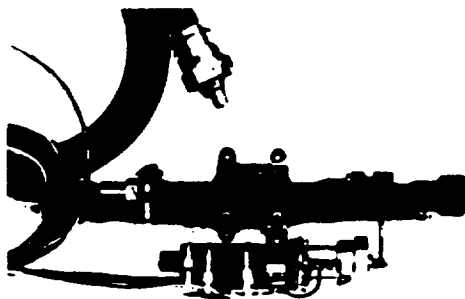 - RESISTOJETS
  - ARCJETS
  - ION

CO-90-4753B

ATD AEROSPACE TECHNOLOGY DIRECTORATE **NASA** Lewis Research Center

AEROSPACE TECHNOLOGY DIRECTORATE

LOW POWER ELECTRIC PROPULSION

ARCJET SYSTEM BASELINED ON TELSTAR IV

CD-90-45148

BEAMED LASER PROPULSION

ON-GOING LERC PROJECTS

- PHASE CONJUGATED/"NONDIFFRACTING" WAVES (I-H)

- H2 LASER ROCKET[1] (CONTRACT WITH COMBUSTION SCIENCE INC.)

(1) SUPPORTED VIA SDIO/IST

SPACE PROPULSION TECHNOLOGY DIVISION   NASA Lewis Research Center

GROUND BASED POWER FOR REMOTE

SPACECRAFT PROPULSION

| PROBLEMS	APPROACH
• ATMOSPHERIC PROPAGATION	• PHASE CONJUGATION
• BEAM SPREADING	• "NONDIFFRACTING" BEAMS

ADVANCED PROPULSION CONCEPTS

NONDIFFRACTING AND PHASE CONJUGATED WAVES

THEORY	EXPERIMENT	RELATED ACTIVITIES
1972 Zeldovich et al (Moscow) Brillouin phase conjugation of of high power laser light	1987 Durnin, Miceli, Eberly (U. Rochester) Demonstration of low power optical Bessel beam propagation (~ 5m)	**Atmospheric Propagation** - U.S. Navy MIRACL laser system - USAF high power CO_2 laser system - Ball Corporation Relay Mirror Expt - SDI applications
1983 Brittingham (LLNL) Nondiffracting pulsed wave solutions to Maxwell's eqns	1989 Ziolkowski, Lewis (LLNL), Cook (U Houston) Demonstration of pulsed nondiffracting acoustic Gaussian waves in water (~ 1m)	**Wavefront Correction** - Fast steering mirrors - Adaptive optics for civilian and military applications
1985 Ziolkowski (LLNL) Analysis of nondiffracting pulsed Gaussian beams		
1987 Durnin (U. Rochester) Analysis of nondiffracting continuous Bessel beams	1989 Shen et al (Harvard University) Demonstrated properties of electromagnetic "missiles" with energy decreasing $< r^{-2}$ (~ 15m)	
	Ongoing Numerous institutions Phase conjugation experiments involving 3 and 4-wave mixing, stimulated Brillouin scattering	

SIGNIFICANT ACTIVITY ON CONCEPTS RELATED TO NONDIFFRACTING AND PHASE CONJUGATED WAVES FOR REMOTELY TRANSMITTED POWER
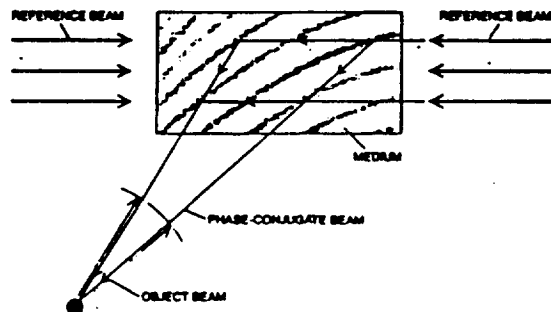

PHASE CONJUGATION

- **ALTERNATIVE TO ADAPTIVE OPTICS**

- **NON-LINEAR OPTICAL EFFECT**

  - **"DYNAMIC HOLOGRAPHY"**

  - **EXACTLY REVERSES DIRECTION, PHASE OF INCIDENT BEAM**

  - **ELIMINATES EFFECTS OF DISTORTING MEDIUM**
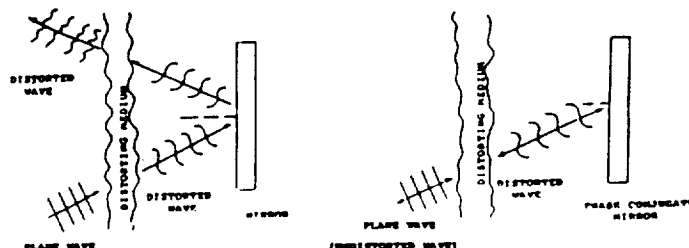
PHASE CONJUGATION

- THREE-WAVE AND FOUR-WAVE MIXING

  EM beam self-interactions
  E-fields in phase, high local intensity
  E-fields out of phase, low intensity
  interference pattern, zones of various refractive indices
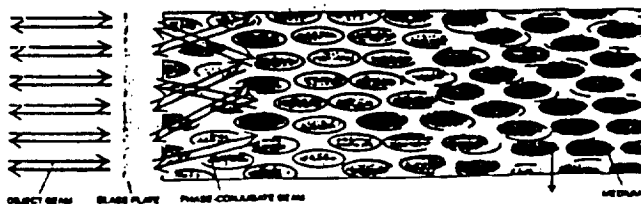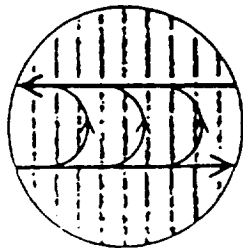 "dynamic holography"

PHASE CONJUGATION

PHASE CONJUGATE METHODS:

- STIMULATED BRILLOUIN SCATTERING

  counterpropagating beams generate sound waves in material
  changes density of material (compression/rarefaction zones)
  periodically changes index of refraction
  reflects incoming light

Space Administration
Lewis Research Center

PHASE CONJUGATION

IDEALIZED PHASE CONJUGATE SYSTEM

Incident Wave

Distortion Causing Media (eg. atmosphere)

Returned strengthened undistorted wave

Distorted Wave

Reflected strengthened Distorted wave

Amplifier (optional)

Increased Distorted Wave Power

Reflected wave

Phase Conjugate Mirror

•Brillouin Scatterers

•Four Wave Mixers
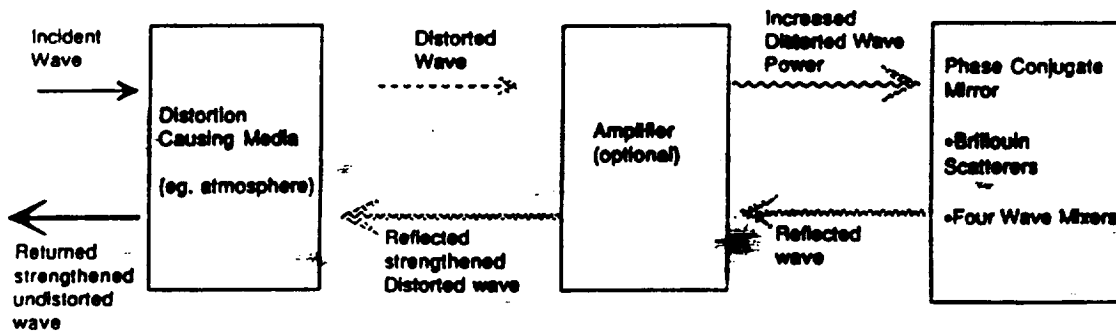
Phase Conjugation

Space Propulsion Applications

low power downlink beam

High power useful uplink beam

Phase Conjugate Mirror and Amplifier
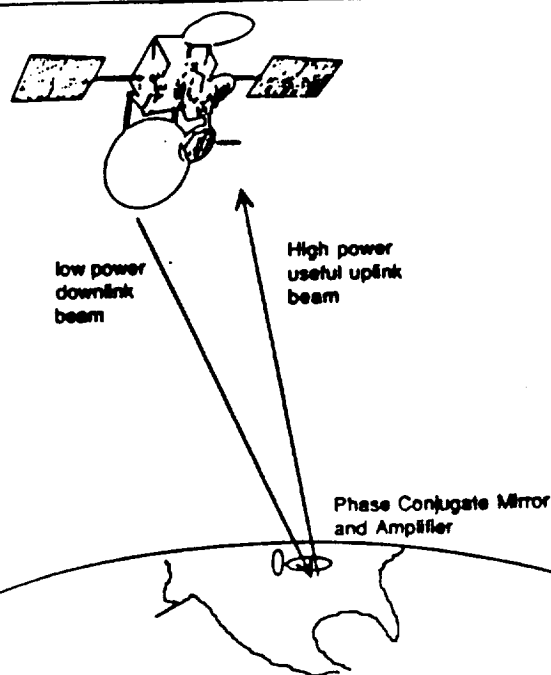
PHASE CONJUGATION

IN-HOUSE PHASE CONJUGATION EXPERIMENTS
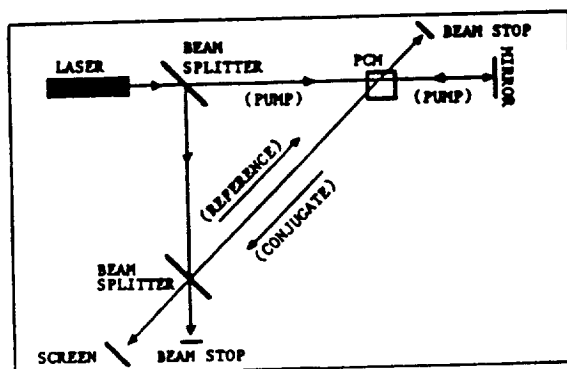
PHASE CONJUGATION

STATUS

- IN-HOUSE FACILITY OPERATIONAL

    - 3,4 WAVE MIXING
    - LOW POWER HeNe LASER
    - $BaTiO_3$ PHOTOREFRACTIVE CRYSTALS

- INTEREST AMONG CIVIL/DOD COMMUNITIES

"NONDIFFRACTING" WAVES

SOLUTIONS TO THE WAVE EQUATION WHICH TRAVEL WITHOUT SPREADING

- PULSED GAUSSIAN WAVES (LLNL)

- CONTINUOUS BESSEL BEAMS (U. ROCHESTER)

- ELECTROMAGNETIC "MISSILES" (HARVARD U.)

- ELECTROMAGNETIC "BULLETS" (HARVARD U.)

DIFFRACTIONLESS/PHASE CONJUGATED WAVES

CONTINUOUS WAVE BESSEL BEAMS

EXPERIMENT*
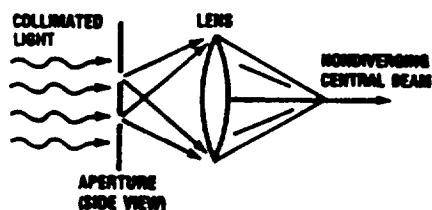
EXPERIMENTAL ARRANGEMENT FOR
CONSTRUCTING BESSEL BEAM DISTRIBUTIONS
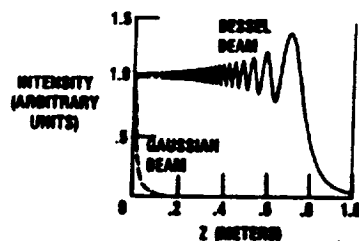
BESSEL BEAM PROPAGATION VERSUS
STANDARD GAUSSIAN BEAM

$$Zmax = R \left[(2\pi/\alpha\lambda)^2 - 1 \right]^{1/2}$$

* J. Durnin, J. Miceli, Jr., J. Eberly, "Diffraction-Free Beams," Phys Rev Let, 58(15), 1987 pp 1499-1501.

CONTINUOUS WAVE BESSEL BEAMS

1). Laser
2). Expanding lens
3). Collimating lens
4). Bessel beam aperture

5). Apperture lens
6). Beam sizing lens
7). Beam diagnostic path
M - Mirror   S - Beam stop
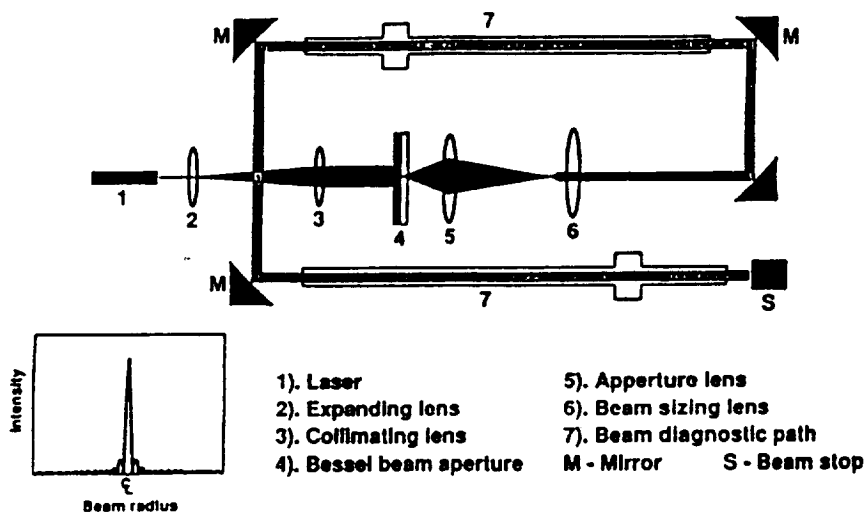
"DIFFRACTIONLESS" WAVES

RESULTS

- **BESSEL BEAMS DIFFRACT**

- **NEW ANALYSIS OF PUBLISHED RESULTS**

  - **PROPAGATION DISTANCE = fD/d**

  - **PUBLISHED RESULTS WORSE THAN DIFFRACTION LIMIT**

"DIFFRACTIONLESS" WAVES

STATUS

- "NONDIFFRACTING" WAVES DIFFRACT

  - UNPUBLISHED NRL STUDY* QUESTIONS OTHER "NONDIFFRACTING" BEAM EXPERIMENTS

HOWEVER

- NEW CONCEPTS TO ENHANCE PROPAGATION DISTANCES

  (a) CHOOSE LENS SYSTEM SUCH THAT $\dfrac{fD}{d} > \dfrac{\Pi D^2}{4\lambda}$

  (b) USE OF PHASE CONJUGATION TO CANCEL WAVEFRONT CURVATURE

- P. Sprangle and B. Hafizi, "Comment on Nondiffracting Beams," to be published in Phys. Rev. Letters

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LASER ROCKET[1]

OBJECTIVE

- BUILD & DIRECTLY TEST A 10KW H_2 LASER ROCKET (AT U OF ILL.)

  - ANCHOR THERMAL & PERFORMANCE MODELS
  - DIRECTLY EVALUATE THRUST VS GEOMETRY & CONDITION

- DESIGN AND FABRICATE A 100KW H_2 LASER ROCKET

(1) SUPPORTED VIA SDIO/IST

- Specific Impulse = 600 - 700 sec
- Pressure = 1.0 atm
- Plasma Efficiency ≈ 35%
- Overall Efficiency ≈ 20%

- Mass Flow = 0.1 g/sec
- Throat D* = 3 mm
- Thrust ≈ 0.5 N
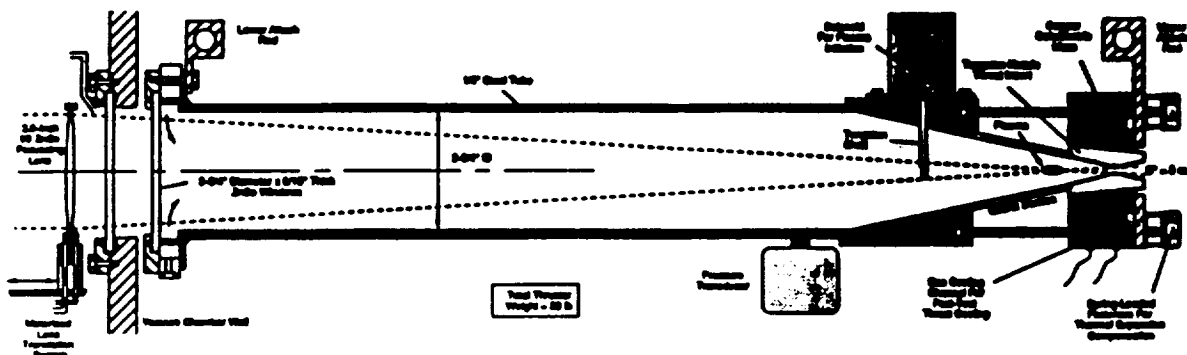
Combustion Sciences, Inc.
Space Propulsion Division

100 kW Thruster Layout

CSI

- Isp = 900 -1000 sec
- Pressure = 1.0 atm
- Plasma Efficiency = 60%
- Overall Efficiency = 45%

- Mass Flow = 0.5 g/sec
- D* = 7 mm
- Thrust = 5.0 N
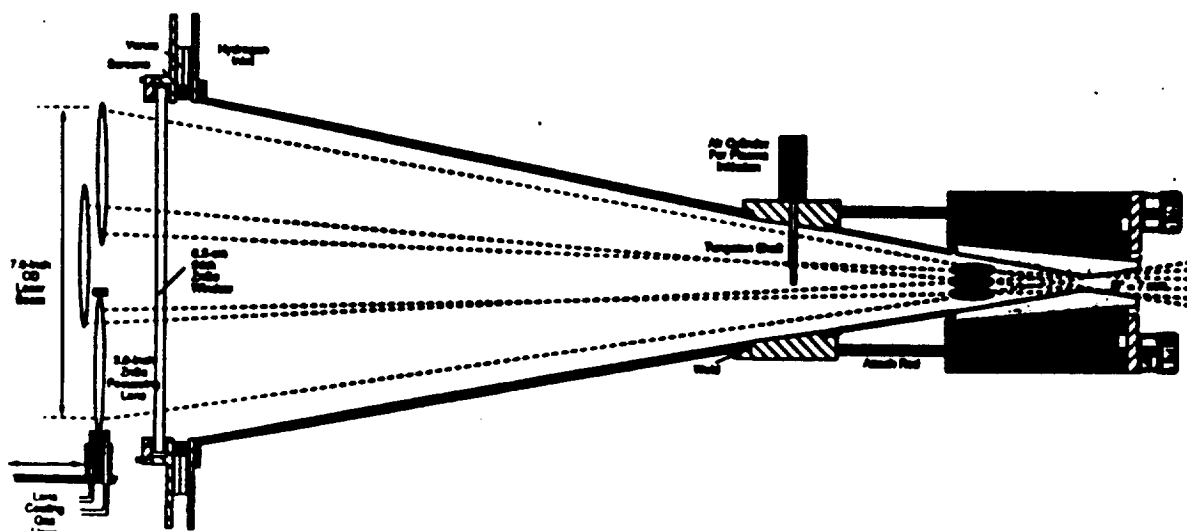
LASER ROCKET [1]

STATUS

- TEST WITH ARGON HAVE DEMONSTRATED:

    - ABSORBTIONS OVER 0.85
    - THERMAL EFFICIENCIES OVER 0.3
    - SUSTAINED MULTIPLE PLASMAS

- H_2 PERFORMANCE MODELS COMPLETED

- 10KW H_2 ROCKET & TEST STAND FAB NEARLY COMPLETE

    - TESTS PLANNED FOR MARCH/APRIL/MAY

- 100KW DESIGN COMPLETE

(1)   SUPPORTED VIA SDIO/IST

LASER ROCKET STATUS[1]

ABSORBTION EFFICIENCY, %
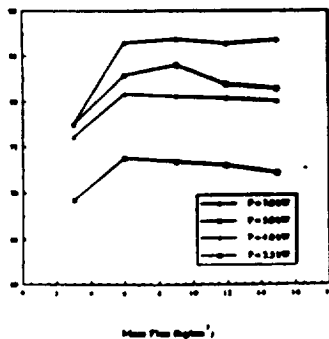
OVERALL THERMAL EFFICIENCY, %
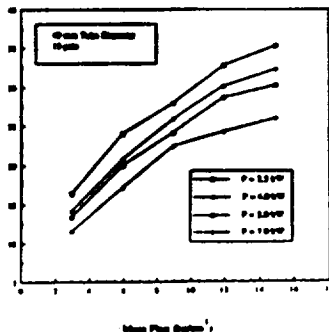
TWO STABLE PLASMAS
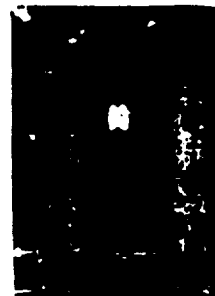
(1)   TESTS ON Ar. UNDER AFOSR-87-0169

LASER ROCKET [1]

PLANS

- COMPLETE 10KW, H_2 ROCKET TEST PROGRAM

- ADVOCATE FOR FAB & TEST OF 100KW, H_2 ROCKET

- INVESTIGATE/ADVOCATE TESTS WITH HIGHER POWER LASERS [2]

  - LABORATORY
  - FIELD

[1] SUPPORTED VIA SDIO/IST
[2] PROPRIETARY INFORMATION AVAILABLE

BEAMED LASER PROPULSION

SUMMARY

- MITIGATION OF SOA IN-SPACE PROPULSION PENALTIES REQUIRES PERFORMANCE IMPROVEMENTS

- POTENTIAL BENEFITS FOR EARTH & PLANETARY PROPULSION

  - VIA GROUND & SPACE BASED LASERS
  - FOR LAUNCH, ORBIT TRANSFER, AND AUXILIARY PROPULSION

- STEADY PROGRESS ON LASERS, PROPAGATION, AND ROCKET CONCEPTS

- MAJOR LEVERAGES FOR NASA PROPULSION

Photovoltaic Energy Converters

Geoffrey A. Landis
Sverdrup Technology
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Photovoltaic Branch

Space Station *Freedom* Photovoltaic Power System
Mass Breakdown per module
(28 kW power produced; 18.75 kW av. user power)

Element	Mass (kg)	Fraction (%)	
PV Blanket	890	24.0	—Array is 1/4 of total system mass
mast	330	8.8	
gimbal	540	14.5	Array plus structure is 1/2 mass
electrical equip.	610	16.6	
thermal control	730	19.6	
misc. integration	610	16.5	
total	3710		

not including:
Batteries: 1300
Charge/disc. unit 290
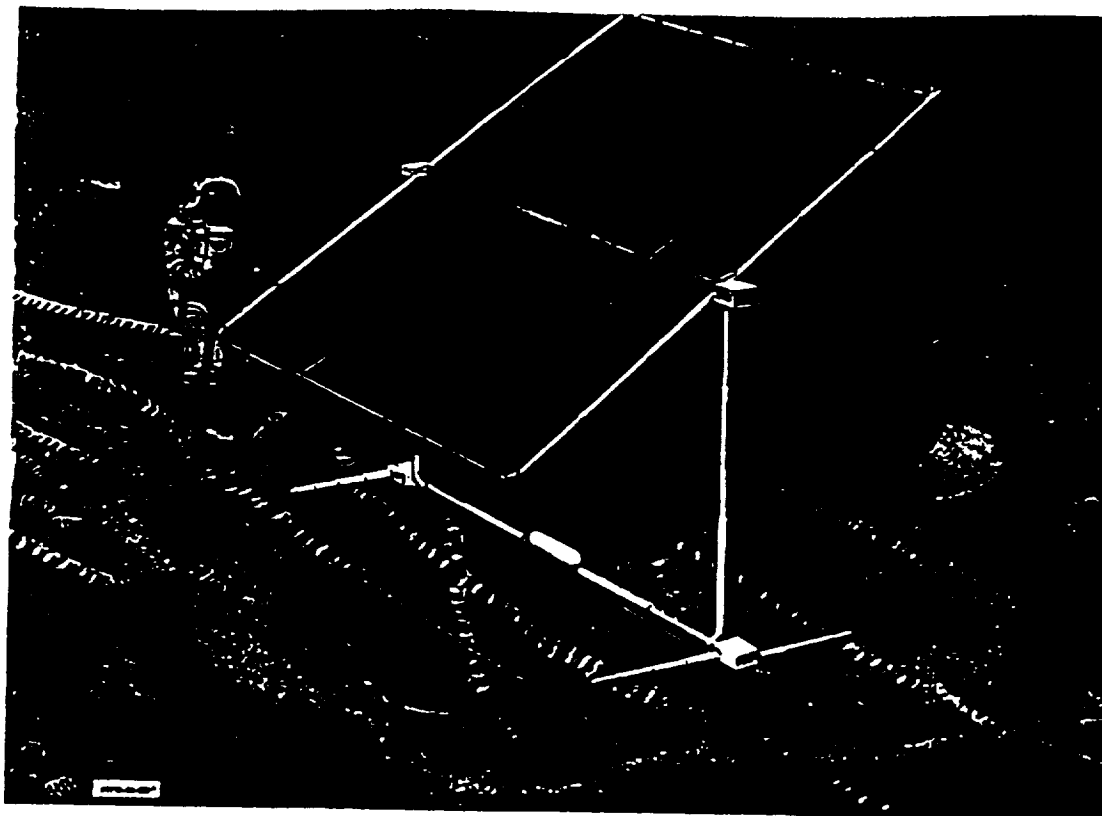
100 kW Photovoltaic Power System for a Lunar Base
(revised to include Balance of System mass = 3x array mass)

Solar Array	cell type	thickness (µ)	efficiency (%)	specific power (W/kg)	Mass array (kg)	total (kg)
Present technology	Si	62	13.5	130	1250	5000
next-generation	GaAs	· 6	18.5	300	540	2150
advanced	Cascade	12	25	450	360	1450
in-situ resource	a-Si	2	10	100	1620	6500

Storage	type	specific energy (W-hr/kg)	mass (kg)	# of
Present technology	Ni-H batteries	14	2,400,000	← 100 HLLV
next-generation	RFC, conv. storage	300	110,000	← 44 Flights
advanced	RFC, cryo storage	1500	20,240	← 8
in-situ resource	composite flywheel	20	1,680,000	

mass is calculated for a 100kW daytime power requirement and 50% night power, with the assumption of 80% storage efficiency.

I-2

Manufacturer	Material	Cell Type	Mounted Cells			Experimental Cells		
			Area [cm2]	Conc.	Eff. [%]	Area [cm2]	Conc.	Eff. [%]
Stanford	FZ Si	High resistivity, back contact	0.64	100	27.2	0.15	140	28.2
	FZ Si	High resistivity, front contact	1.58	130	25.3			
UNSW	FZ Si	Low resistivity, prism covered*	1.58	125	25.2			
	FZ Si	Laser grooved	20.0	20	18.9			
AstroPower	CZ Si	Low resistivity, prism covered*	39.6	20	17.8			
Solarex	FZ Si	Low resistivity, prism covered*	1.58	150	21.5			
	CZ Si	Low-resistivity, prism covered*	38.4	20	20.2			
	PX Si	Low resistivity, prism covered*	39.5	20	17.5			
SERA	FZ Si	High resistivity, back contact				0.065	65	23.9
SPIRE	FZ Si	Low resistivity, V-grooved				0.25	124	20.0
Varian	GaAs					0.126	403	28.1
	GaAs	Prism covered*				0.126	206	29.2
SPIRE	GaAs					0.317	200	28.7
Sandia/ Varian/ Stanford	GaAs/Si	Mechanically stacked, multijunction				0.317	500	31.0
Boeing	GaAs/GaSb	Mechanically stacked, multijunction				0.053	100	34.2

* Prismatic cover technology supplied by ENTECH
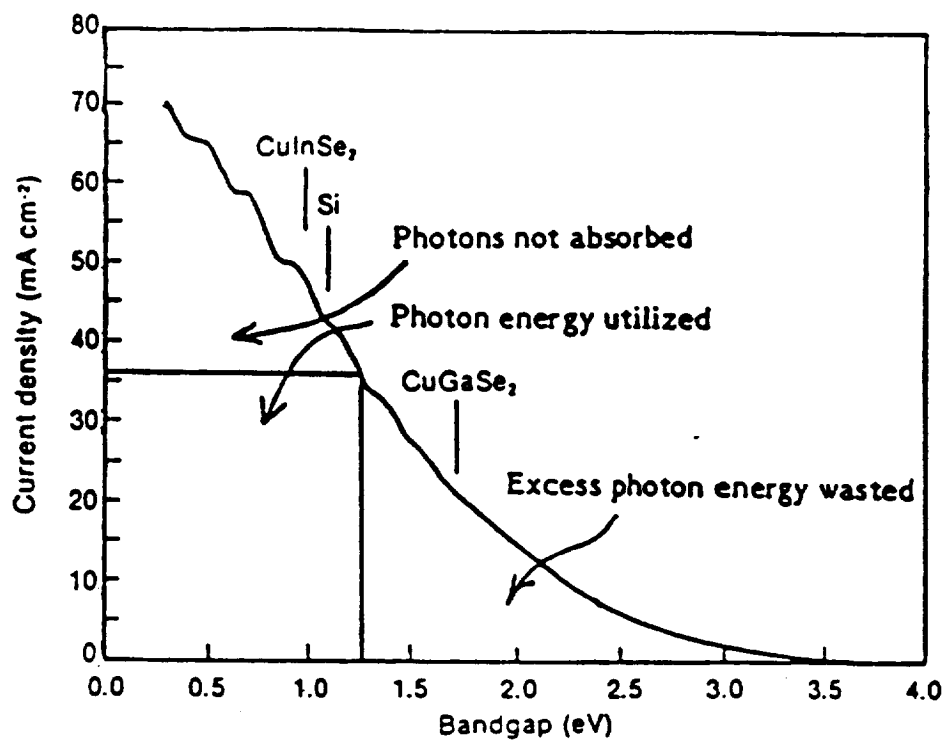
1A   The photon utilization of a single junction cell
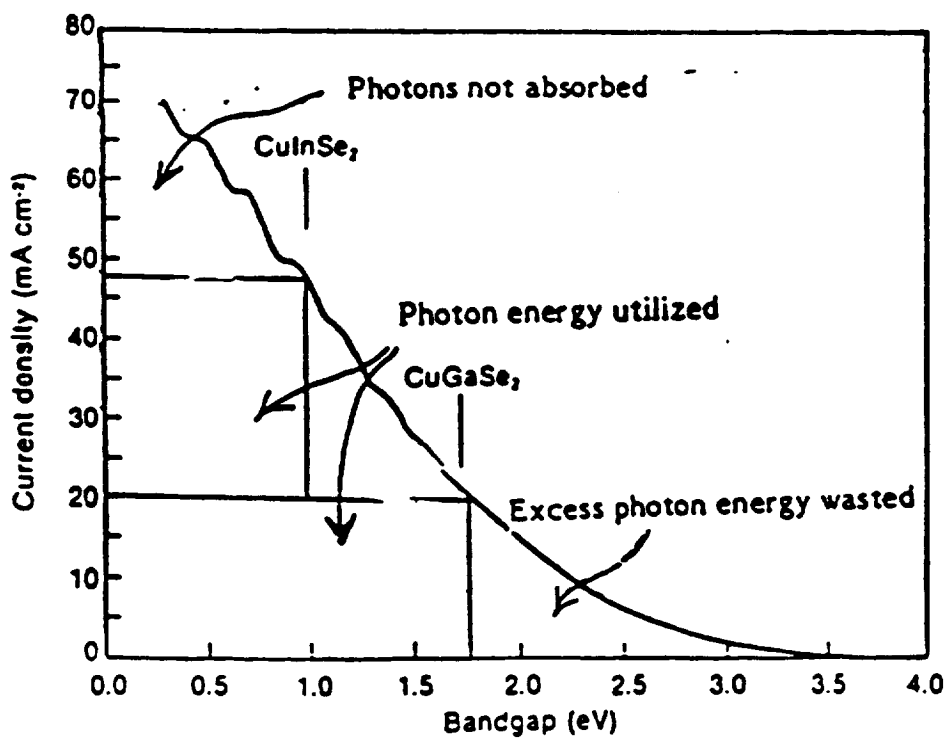
1B   The photon utilization of a two junction cell

I-4

Figure 1.   Integrated Photon Flux vs Energy
for AM1.5 Global (37° tilt) (963 W/m²)

1X, AM 1.5

Voc (volts)

InGaP

GaAsP

AlGaAs

GaAs

InGaAs   InP

Si
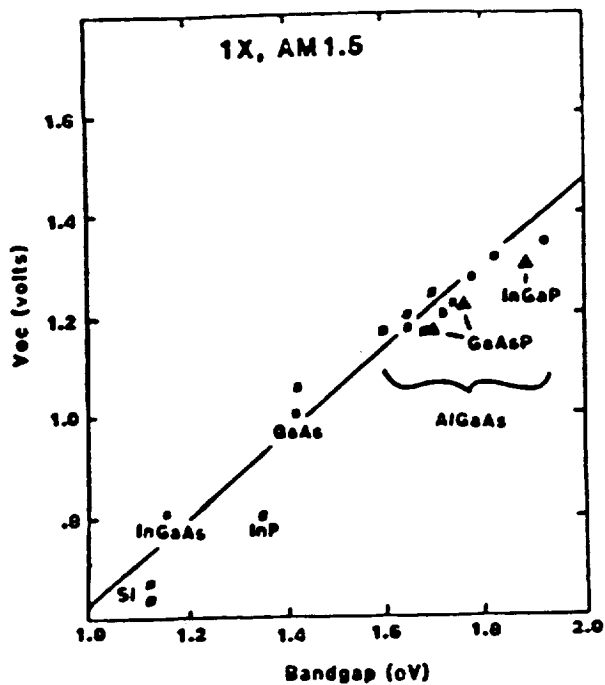
Bandgap (eV)

A plot of reported values of V_{oc} for various III–V solar cells

ACHIEVABLE EFFICIENCY FOR A SINGLE JUNCTION SOLAR CELL
AS A FUNCTION OF THE BANDGAP OF THE MATERIAL
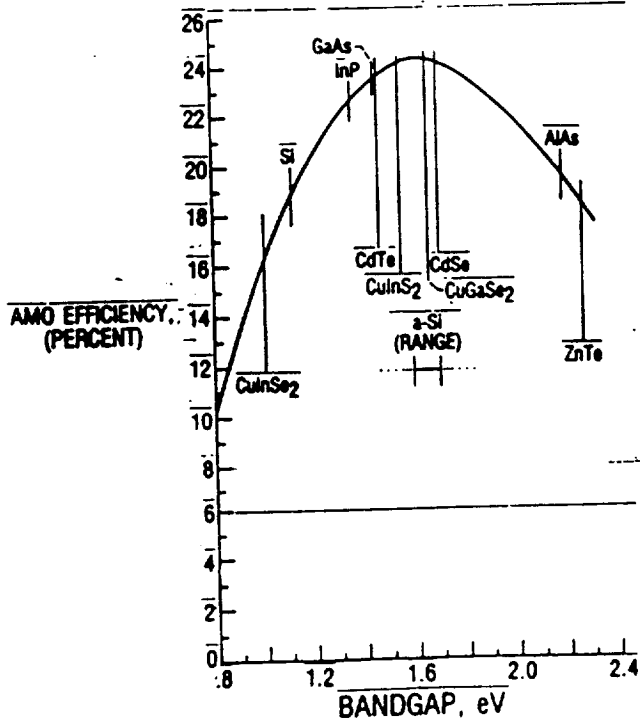
GaAs
InP

Si

AlAs

CdTe   CdSe
CuInS2   CuGaSe2

AMO EFFICIENCY,
(PERCENT)

a-Si
(RANGE)

ZnTe

CuInSe2

~1 sun intensity

BANDGAP, eV

CD-89-41509

I-5

Conc = 99.84 suns
Voc = 1.123V
Isc = 0.1827A
Max power = 0.1728W
Imp = 0.175A
Vmp = 0.987V
Efficiency = 23.88% (AM0 simulator)
Fill factor = 0.84
Temperature = 25° C
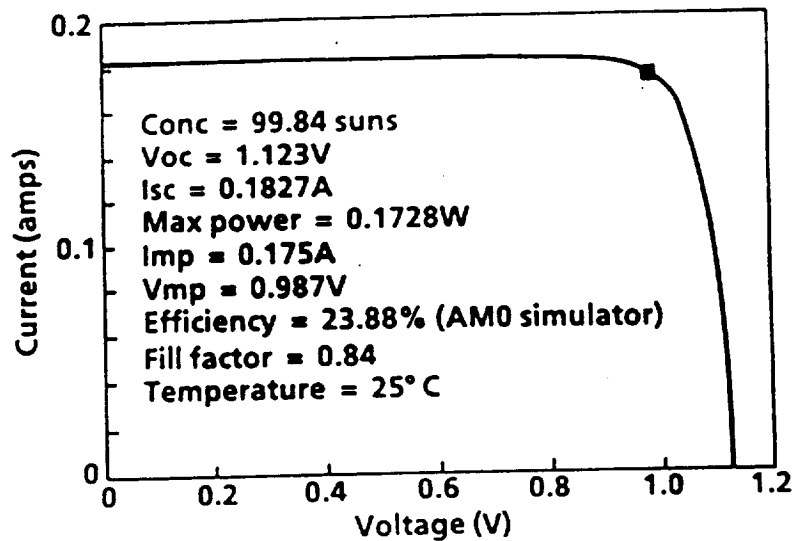
The solar cell power equation:

$$P = I_{sc} \cdot V_{oc} \cdot CFF$$

P = power

I_{sc} = short circuit current
I_{sc} is linear in intensity

V_{oc} = open circuit voltage
V_{oc} is logarithmic in intensity
$V_{oc} = V_{oc} + 25 \text{ mV } [\ln (I_{sc}/I_0)]$

CFF = curve fill factor
CFF varies between about 0.75 and 0.9
increases slightly with V_{oc}
decreases dramatically when cell is resistance limited

Efficiency Vs. Concentration Ratio
for GaAs Cells

Sandia flash
simulator
measurement

Typical space
concentration
ratio

Efficiency (%)
(AM0)

AM0 concentration

No
concentration
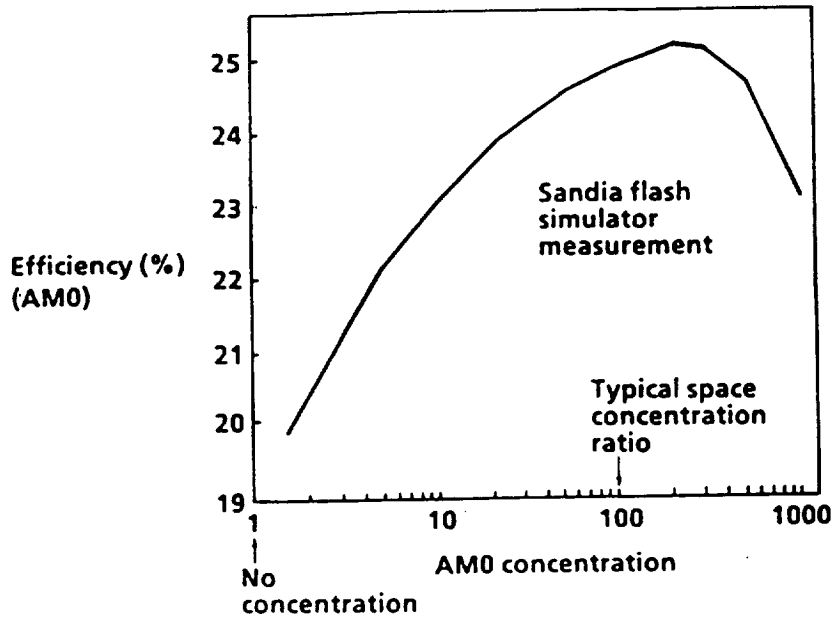
December 4, 1989 8:57 AM HTC/479-099h
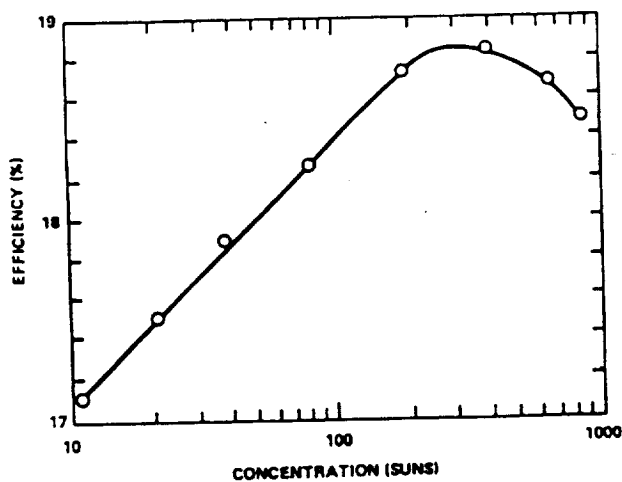
Plot of efficiency vs. concentration (AM 1.5) of a 1.72 eV AlGaAs concentrator
subcell grown on a GaAs substrate. The peak power conversion efficiency is 18.8% under
400 Suns, and the efficiency is 16% under 1 Sun conditions.

$$(\lambda_{cutoff} = 720 \, nm)$$

I-7

Transparent GaAs External QE

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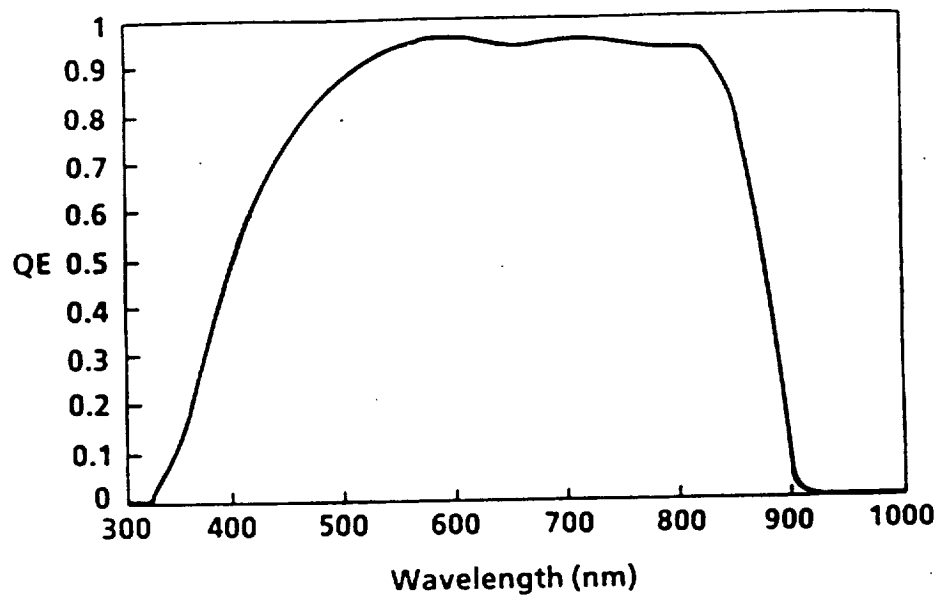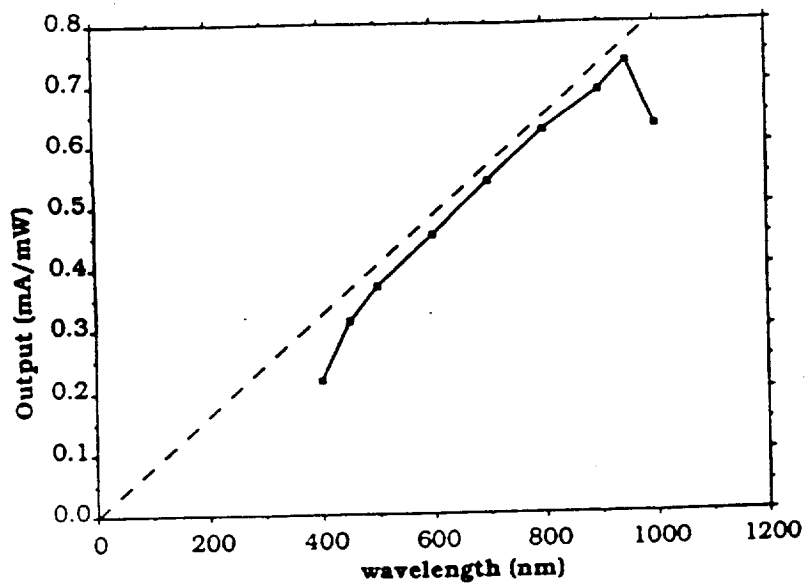
Figure 1. Measured output of a standard silicon solar cell as a function of
incident wavelength. The dashed line indicates the ideal (unity quantum
efficiency) spectral response.

$$(nb: \lambda(\mu) = 1.24/E_g)$$
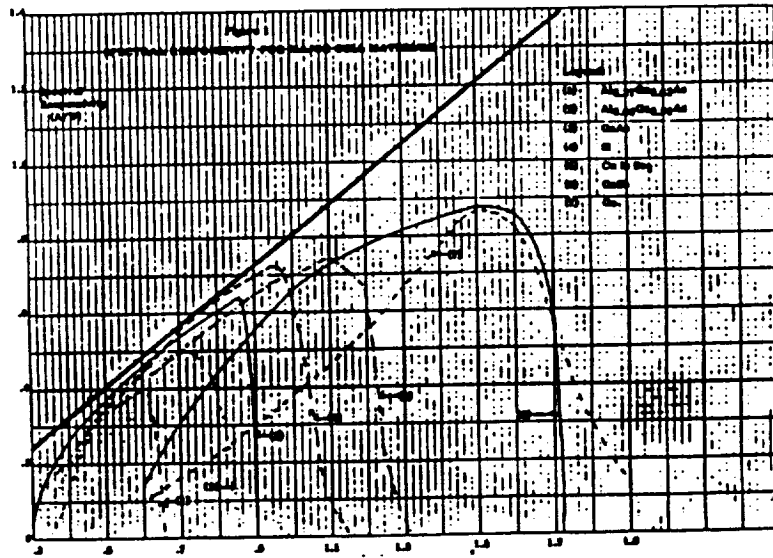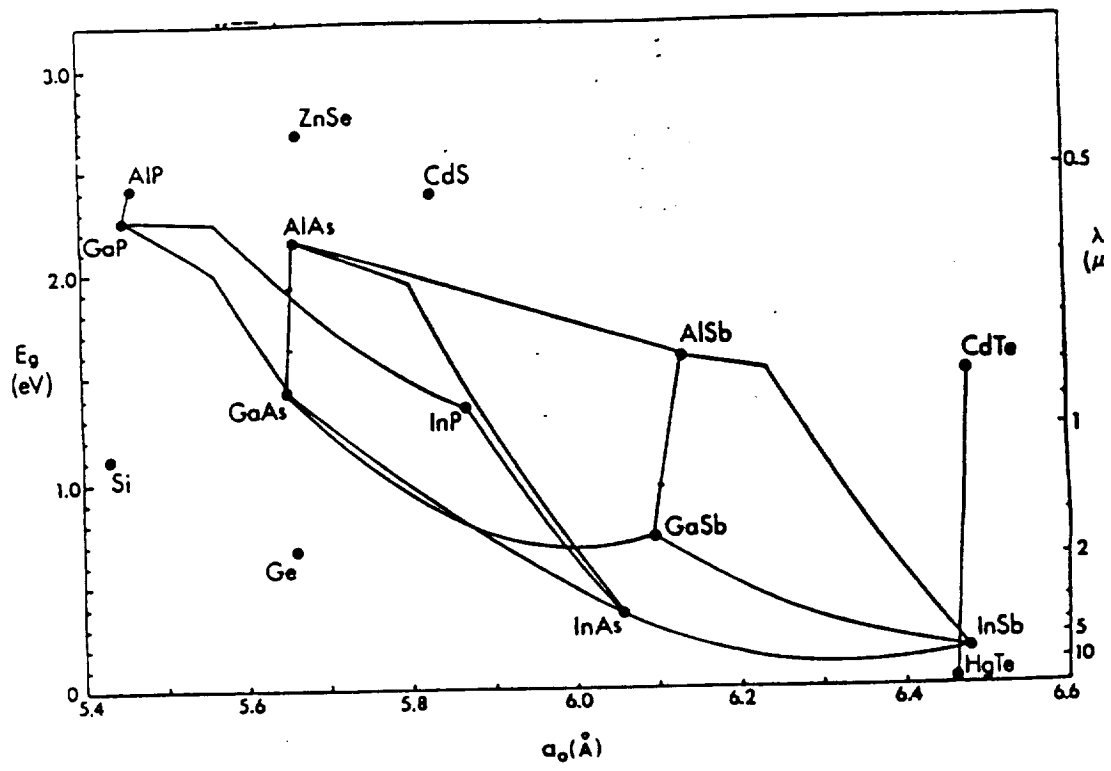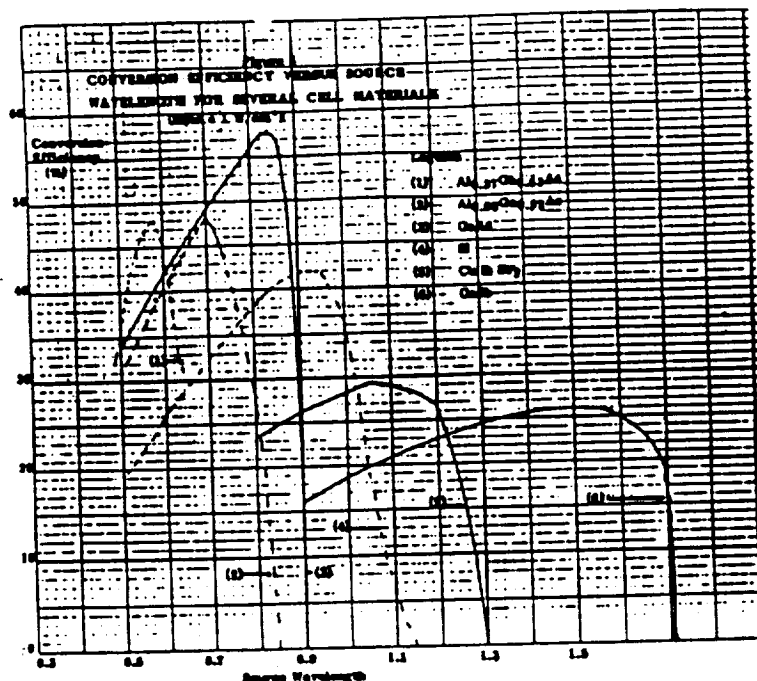
LUNAR DAYTIME

Calculating solar cell power for monochromatic light from solar cell data:

1. Calculate I_{sc} from spectral response times intensity

$$I_{sc}(\lambda) = SR(\lambda)(mA/mW) \cdot I(mW/cm^2)$$

2. Calculate effective concentration ratio

$$X(effective) = I_{sc}(\lambda)/I_{sc}(1\ sun)$$

3. Calculate power from curve of efficiency vs. intensity

$$P = 135\ mW/cm^2 \cdot \eta_{AMO}(X)$$

$$P = 100\ mW/cm^2 \cdot \eta_{AM1.5}(X)$$

Note: Spectral response can be calculated from quantum efficiency

$$SR(mA/mW) = QE \cdot 1240/\lambda(nm)$$

If efficiency vs intensity information is not available, efficiency can be approximated as long as series resistance is not significance by assuming

$$V_{oc} = V_{oc}\ (1\ sun) + 25\ mV\ \ln(X)$$

Solar cell efficiency:

$$\frac{1}{P} \frac{dP}{dt} =$$

	Loss at 90°C
Silicon cell: 0.33%/°C	23%
GaAs cell: 0.25%/°C	17%

Cascade cells: ~ 0.5%/°C to 0.7%/°C

(depends on technology)

Temperature: LUNAR DAYTIME

calculated array operating temperature

(noon)   ~90°C   (depends on efficiency)

Operating temperatures of instrument packages
left on moon (peak)

   Apollo 11   88°C
   Apollo 12   78°C

> Array temperature will be higher than test
temperature — performance will decrease

Conservative and optimistic projections for future efficiency (in percent)

Material	current	---future--- (conserv.)	(optim.)
Si	19	19.5	22
GaAs	21.4	22	25
CuInSe$_2$	11.2	12	13
Opt. Thin-film	8.6	12.5	15
T-F Cascade	12.5	18	20

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Specific power for conservative and optimistic projections for future efficiency (does not include coverglass)

Material	thickness (microns)	substrate (microns)	current (kW/kg)	---future--- (conserv.) (kW/kg)	(optim.) (kW/kg)
Si	60	-	1.8	1.9	2.2
GaAs	60	-	0.9	0.9	1.0
CuInSe$_2$	3	6	7.0	7.5	8.1
Opt. Thin-film	3	6	5.3	7.8	9.4
T-F Cascade	6	6	3.9	5.6	6.2

Advantages of Thin Film Solar Cells

(1) High Radiation Tolerance
(2) High Specific Power, potentially >1 kW/kg
(3) Large Area solar cells with integral interconnects
(4) Flexible blankets
(5) Large (by space power standards) body of array
    manufacturing experience
(6) High tolerance to micrometeroid or debris impact
(7) Low cost

Disadvantages of Thin Film Solar Cells

(1) Lower efficiency
(2) Lack of spacecraft experience
(3) Lack of AMO data
(4) Not currently produced on lightweight substrates

Thin Film Photovoltaics: The Choices

Amorphous Silicon ("a-Si")	Well studied 15 MW+ manufacturing capacity. Demonstrated on thin substrates Light-induced degradation ~10% High E_g
Copper Indium Selenide ("CIS")	Emerging material Highest efficiency in a thin film solar cell to date Not demonstrated on thin substr. Low E_g
Tandem a-Si on CIS	"Holy Grail": efficiency of 15-20% possible materials demonstrated seperately; Tandem only demonstrated in mechanical stack to date

element	material	mass (gr/m^2)	
cell	1.9μ α-Si	2.7	back Al thinned to 2000 Å
substrate	7μ Kapton	10.8	
total		13.7	

efficiency: 7.5% (AMO)   specific power 7500 W/kg
with 25μ glass cover: 1500 W/kg

All-lunar materials:

cell	1.9μ α-Si	2.7	back Al thinned to 2000 Å
substrate	7.5μ steel	60	
total		62.7	

efficiency: 7.5% (AMO)   specific power 1650 W/kg
with 25μ glass cover: 880 W/kg

Front surface grooves

Rear surface grooves
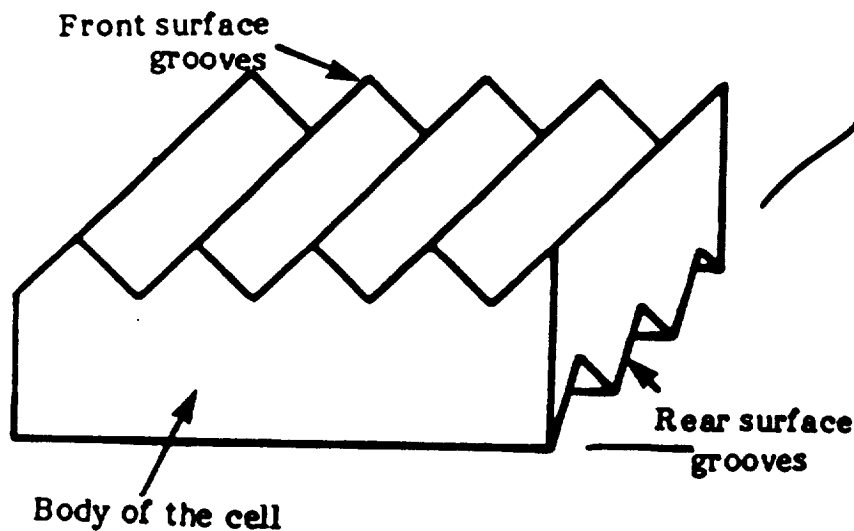
Body of the cell

'ig. 42: Proposed light-trapping structure utilizing V- Grooves etched on 1e cell front and back surfaces
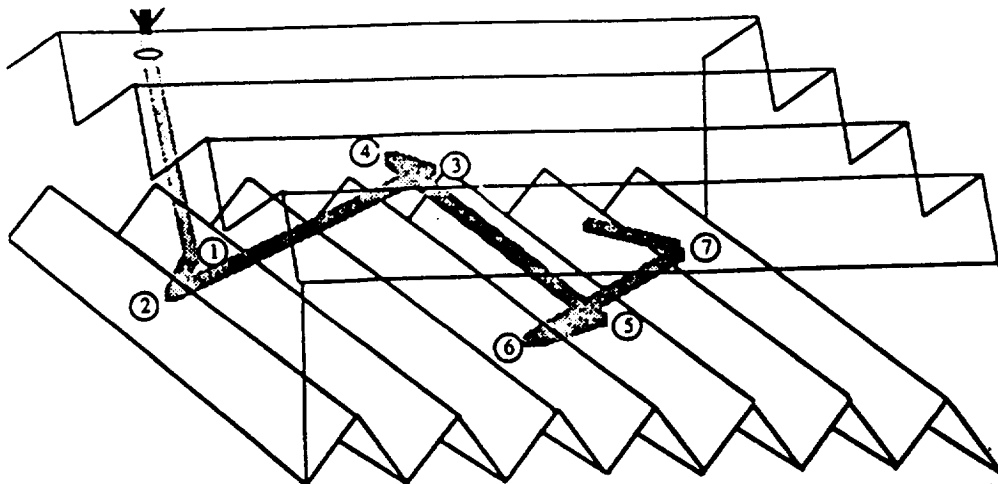
Fig. 43: Typical Light Path in Cross-grooved Structure
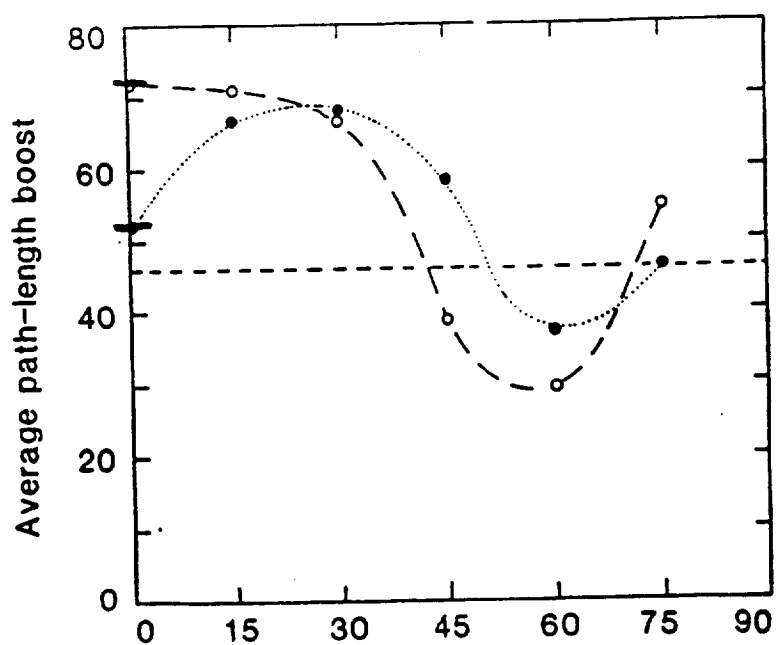
Fig. 48: Dependence of the Confinement Efficiency on the Incident Light Angle for the Grooved Cell Structure [from Campbell and Green, Ref. 59]

Dashed line is Lambertian confinement; filled and open circles are cross- grooved structure with different ratios of groove width to thickness

1. The overwhelming majority of the mass of a PV power system for the moon is the mass of the energy storage system required to power the base over the 354 hour night.

2. Balance of systems (power management, etc.) adds a significant amount to the mass of a power system.

3. For all cell types, efficiency rises slowly as intensity increases as long as temperature is kept constant. If temperature is not controlled, efficiency decreases with increased intensity.

4. Solar flares will reduce efficiency due to radiation damage. This can be reduced by shielding the cells with glass, or by chosing radiation resistant solar cell types such as InP.

5. Solar cells optimized for conversion of monochromatic light will also have good efficiency for sunlight for most materials of interest.

Conclusions
(continued)

For cells near the optimum bandgap for solar conversion, monochromatic light efficiency is twice the solar spectrum efficiency
If a material is chosen at optimum bandgap for monochromatic light, the theoretical efficiency will be about 50% regardless of wavelength (*however*, for very long wavelengths active cooling will be required!)

GaAs solar cells have the highest efficiencies of present cells. Conversion efficiency is ~50% for laser light at intensities of 1 kW/m^2 near the optimum wavelength of about 850 nm. The efficiency decreases sharply with longer wavelength, and linearly with shorter.

Silicon solar cells are cheaper and have peak response at about 950 nm. Current cells are not optimized for laser power conversion and would have monochromatic conversion efficiency of about 30%-40%. Light-trapping cells with optimized long wavelength response could have peak efficiencies approaching 45% at about 1000 nm.

Thin-film solar cells will have efficiency for monochromatic light of 10-20%, but are extremely cheap and potentially very light weight. This technology is not yet space qualified, but is advancing rapidly.

Wavelengths outside the range of about 600-900 nm will require new materials to be developed if maximum efficiency is to be achieved.

-Laser provided power at night only

-Array intercepts 10% of the incident power
array produces 200 kW day power
thin plastic reflectors augment area of array during night by 4X

-lens (or mirror) on Earth radius 1 m; laser wavelength 400 nm
illuminated area on moon 31,000 m^2

-50 kW power at moon
2 MW of power needed (forty 50-kw lasers)

-Two choices: either have multiple laser stations to present
continuous illumination, or else storage is required for 12 hours
when laser is out of line of sight. However, 12 hours of storage is
still about 30 times better than the 354 hours required for the full
lunar night!

ref: G.A. Landis
"Solar Power for the Lunar Night"
NASA TM-102127, 1989

"Moonbase Night Power by Laser Illumination"
AIAA J. Propulsion and Power, to be published

Solar
cells

lightweight
Aluminized Kapton (8µ thick)
reflectors
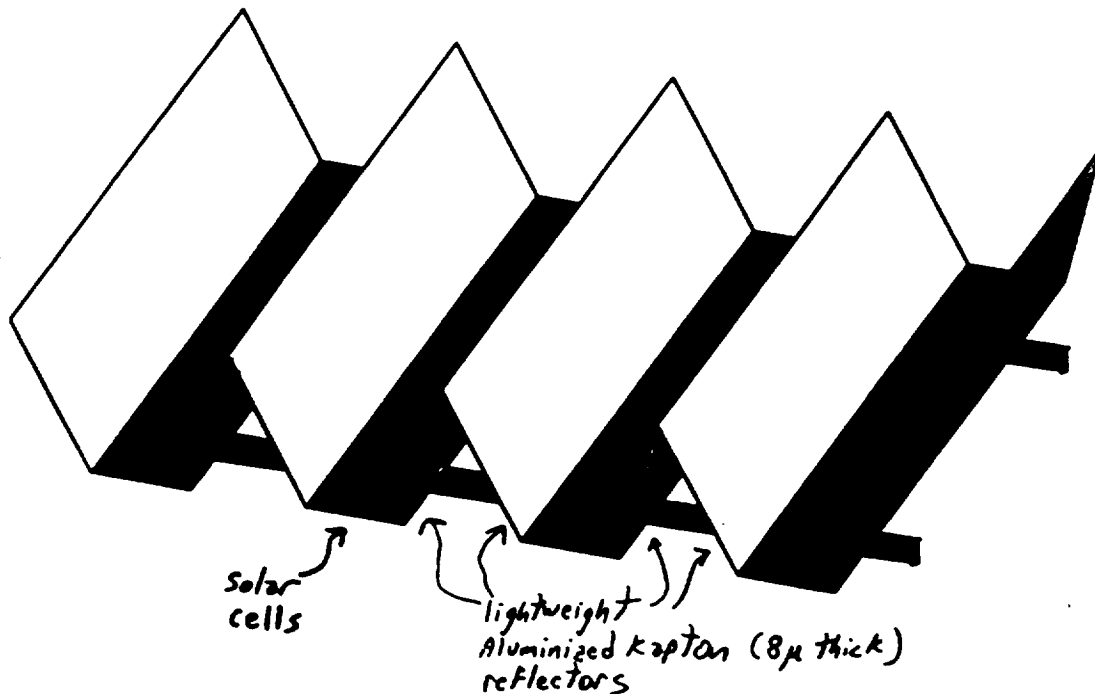
Reflector-Augmented Solar Array

Solar Power for the Lunar Night

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Lewis Research Center
Cleveland, Ohio

NASA

SOLAR POWER FOR THE LUNAR NIGHT

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National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Abstract

Providing power over the 354 hour lunar night provides a considerable challenge to solar power concepts for a moonbase. The paper reviews concepts for providing night power for a solar powered moonbase. The categories of solutions considered are electrical storage, physical storage, transmitted power, and "innovative concepts". Electrical storage is the most well-developed option. Less developed electrical storage options are capacitors and superconducting inductors. Physical storage options include storage of potential energy and storage of energy in flywheels. Thermal storage has potentially high energy/weight, but problems of conduction and radiation losses during the night need to be addressed. Transmitted power considers use of microwave or laser beams to transmit power either from orbit or directly from the Earth. Finally, innovative concepts proposed include reflecting light from orbital mirrors, locating the moonbase at a lunar pole, converting reflected Earthlight, or moving the moonbase to follow the sun.

[*]National Research Council—NASA Research Associate.

1. Introduction

The possible options for the power source are solar (either photovoltaic or dynamic), or nuclear. There is interest in making a lunar base solar powered, due to the considerable political and technical barriers, real and perceived, to the use of nuclear power. A permanent lunar base is a considerable challenge for solar power technology, due to the necessity of providing fourteen days of power during the darkness of the lunar night. While some base systems can be shut down or run at reduced power during the night, other systems, such as running greenhouse lights, providing air recycling, etc., may even have increased power consumption during the night.

For a typical moonbase design, the storage required for lunar night operation will be the major mass component of the electrical system. For conventional Ni-H batteries with 32 W-hr/kg (current technology), a 100kW daytime power requirement and 50% night power, one estimate puts the mass of the batteries alone at over a million kilograms [1,2]. In contrast, the photovoltaic panels themselves would be quite light: 500 kg for an APSA technology array with thin GaAs cells [1], and potentially even less for advanced thin-film technologies [3,4]. Clearly, then, higher performance concepts for power during the lunar night would be desirable.

Due to the high cost of delivering mass to the moon, the important engineering figure of merit for an energy storage system is the energy to weight ratio, or specific power, measured in watt-hours per kilogram (W-hr/kg). A similar consideration is applicable to beamed power and innovative power systems, where the effective stored energy is equal to the power times 354 hours. Other important figures are the ratio of charging energy to energy output during discharge, or energy efficiency, and the lifetime, both of which must be high; and the required maintenance, which should be low. Of considerably less importance is the capital cost, since the transportation cost is likely to dominate the total cost.

Finally, for long-range use it is important that the system can be manufactured from materials which can be mined and refined from available lunar resources, since the long-term evolution of the lunar base is likely to be by a "bootstrap" process. It is widely accepted that solar cells can be manufactured on the moon, however, for a self-sufficient lunar base, it is important that the energy storage (or transmission) capability also have the possibility of being locally manufactured.

This paper briefly surveys and discusses the possible options for night power. The paper is intended as a brief and perhaps superficial survey of the concepts proposed, and should not be taken for a comprehensive critical review, which has not to date been written.

The concepts discussed can be divided into storage technologies and continuous power concepts. Storage includes electrical storage methods and physical storage methods, while continuous power concepts can be roughly categorized as transmitted power systems or "innovative concepts".

2. Electrical Storage

Electrochemical Storage

The existing state of the art in electrical storage for spacecraft is the nickel-hydrogen (Ni-H) cell. The specific energy for the best cells currently on spacecraft is 32 W-hr/kg (Intelsat-VI) [5], with 45 W-hr/kg in the prototype stage [5], and up to 75 W-hr/kg projected [6]. Lithium and sodium-sulfur batteries, neither of which are currently in use, have the potential similar specific energy, up to a maximum of about 100-150 W-hrs/kg [7].

A potentially lower mass technology is the hydrogen/oxygen regenerative fuel cell. "Regenerative" indicates that water produced during the discharge is electrolyzed by the solar panels during the charging cycle. The technology is not fully developed. The highest mass element is the pressure tank required to store the reactant gasses. Current technology uses steel pressure tanks, with a specific power on the order of 50 W-hr/kg. Next-generation technology will use composite (Kevlar) filament-wound tanks, with specific power on the order of 500 W-hr/kg. Even with composites, the tanks still comprise nearly 60% of the system mass. Future technology may use cryogenic reactant storage, with up to 1500 W-hr/kg [8]. The technology will require a cryogenic refrigeration plant to liquefy the reactant gasses and store them at cryogenic temperatures.

Capacitive and Inductive Storage

An alternative to electrochemical storage is energy storage in capacitors or inductors. In a capacitor, energy is stored as electrical charge on layers of metal separated by thin insulator film. Capacitors have lower specific energy than electrochemical storage, typically under 1 W-hr/kg, although capacitors of up to 10 W-hr/kg are possible, and 20 W-hr/kg is seen as a reasonable goal in the timeframe 2000+ [7]. An attractive possibility for the long term could be capacitors manufactured using aluminum as the metal and SiO_2 or Al_2O_3 as the insulator, both refined from locally available materials.

The amount of capacitance required would be very large. For example, at a storage voltage of 10 kV, 100 kW of storage for 354 hours would require over two thousand farads of capacitance, a very large figure by conventional electronic standards.

In inductive storage the energy is stored as a magnetic field associated with a continuous current flow. To avoid resistive losses, an inductive storage system would necessarily have to be made using high critical field superconductors, and such storage is often referred to as "Super-conducting Magnetic Energy Storage System", or SMES. Recent advances in high temperature superconductors (HTS) make inductive storage more reasonable [7], since the inductors could possibly be shielded from sunlight and Earthlight and need no refrigeration. The recently discovered class of high-temperature superconductors are composed of materials that, except for oxygen, are not generally found on the moon. However, HTS technology needs to be significantly advanced in terms of critical field, current densities, mechanical strength and stability, and the ability to make the materials in the form of wires.

Typical inductive storage projects using conventional (Nb_3Sn) super-conducting technology have specific energy of about 0.5 W-hr/kg. For example, a recent design for a 14 kW-hr demonstration superconducting inductive energy storage ring had a coil mass of 26 tons [9]. However, a design study for a 5 GW-hr storage ring estimated a mass of 50,000 to 270,000 tons (depending on the design) [10], for a specific energy of 18-100 W-hr/kg. This mass is for the Nb_3Sn superconducting coil alone; additional elements such as mechanical supports are likely to reduce this value to only a small fraction of the coil-alone value.

The ultimate limit to the specific energy of an inductor is set by the strength of materials, which must withstand the magnetic forces on the system. The upper limit is about 300 W-hrs/kg at structural failure, assuming that composite materials are used for the strengthening elements. Current storage systems do not approach this limit.

3. Physical Storage

Potential Energy Storage

On Earth, the most common energy storage medium used by electrical utilities is Earth's gravitational field, where the storage method is to hold water behind a dam, running it through turbines when power is desired. Due to the absence of water on the moon, this is not a usable solution. A variation of this concept suitable for the moon would be to store and release energy by lifting and lowering lunar rocks, *e.g.*, on cables suspended from a tower, raised and lowered by an electric winch. The advantage is that the storage medium, rocks, are easily available and need no processing. The problem is that it is difficult to store much energy this way--the moon's gravity is just too feeble. The storage capacity is about 1 kW-hr for each 150 ton boulder lifted 30 meters.

Energy storage in the form of compressed air has also been studied as a method of load-levelling for electrical utilities on Earth. These applications typically use an auxiliary combustion stage to heat the gas during the discharge phase [11]. Storage is typically in natural caverns or mines. Energy storage without auxiliary combustion is not competitive on Earth [12]. This is unlikely to be a useful storage system on the moon, since auxiliary combustion is not possible, the gas itself would have to be brought from the Earth, at least for the early use (for expansion, lunar generated oxygen may be an option), and leakproof natural lunar caverns are unlikely to be available at the moonbase site.

Thermal storage is being considered for the solar-dynamic power systems planned for use on the phase two version of space station "Freedom" [13]. In this storage option, energy is stored in the form of heat, typically in a phase-change material. The heat storage itself is expected to have specific energy of ~250 W-hr/kg [14], although only a fraction of this will be accessible as electric power. Thermal storage is a much more likely option for space station applications, where the storage required is only 30 minutes, than for the moon, where the material must remain hot for fourteen days. This is a viable option if the primary power system for the lunar base is solar dynamic. Since the energy losses are likely to be dominated by radiation loss, a low-temperature system is more amenable to long period storage than a high-temperature system.

An alternative version of thermal storage is to use lunar rock as the storage medium. This drastically decreases the amount of material which has to be brought from Earth. In a low-temperature thermal system, an insulated pit containing lunar rocks would be heated to a storage temperature of ~300° C by embedded heat pipes carrying solar energy during the lunar day, and this energy would be used to run a heat engine during the night [15]. In a high temperature system, the regolith could be heated to 1700°K [16] and thermal radiation from the hot rock used to illuminate a photovoltaic array optimized for IR conversion. Radiation not usable by the solar cells could be reflected back to the source. Eder [16] estimates that, neglecting losses, a volume of regolith 4-5 m in each dimension should suffice to provide 100 kW of night power.

The difficulty of this system is insulating the rock bed against heat loss to the surrounding lunar soil. Higher temperature systems have considerably greater difficulties with both radiation and conduction losses, although the higher energy densities allow more compact storage and thus reduced surface area. This problem has not to date been analyzed in depth. Solar furnace designs for melting regolith are discussed by Lewis [17], who estimates that a 21 ton mass of regolith glass will cool from 1700°K to 1200°K in roughly 1.5 days [18]. However, if this could be done without a large amount of required mass, the system weight could be considerably lower than that of other storage methods.

Losses in thermal systems decrease as surface to volume ratio decreases and thus are less important as the system size increases. The cooling time of larger mass systems scales proportionately to the cube root of the mass. Thermal storage thus becomes increasingly attractive for larger base sizes.

Since a manufacturing facility is likely to use many high-temperature processes such as magma electrolysis or glass manufacturing, the waste heat of the processing could also be used for the electrical power [17,19].

If thermal storage is to be considered, issues of conduction and radiation losses during the night must be examined in detail. Because of the long storage times, thermal storage is unlikely to be competitive using present day materials, but may be possible with improved materials.

Flywheel Storage

A final possibility is storage as kinetic energy by use of a flywheel. The best current technology flywheels have specific energy of about 20 W-hrs/kg. A composite flywheel with specific energy of 120 W-hr/kg at failure has been demonstrated [20] (not counting support systems, bearings, motor/generator, etc.) Counting a factor of three for safety margin and 50% additional mass for support systems, this comes to about 36 W-hrs/kg. These values are considerably below the theoretical limits of advanced composite materials [21], about 300 W-hrs/kg at failure.

A problem with flywheels for terrestrial storage is the requirement for vacuum. This is not a problem on the moon, where the vacuum is available. A second problem is that a flywheel must have a containment system, to prevent high-velocity fragments from causing injury in case of a catastrophic failure. On the moonbase, the flywheel can easily be placed below ground level, where this is also not a problem.

It is likely glass fiber for a composite flywheel could be manufactured from available materials [19], albeit with ultimate strength less than that of advanced composite fibers such as Kevlar or graphite. Materials for the polymer matrix, however, is not likely to be available. If a metal matrix, such as titanium or aluminum, could be used, then flywheel storage is an attractive option for future storage based on locally manufactured, all-lunar material technology.

Flywheels have losses due to residual friction, eddy currents, etc., which in some cases can be quite large. These losses would have to be reduced to below about 0.2% per hour for flywheels to be useful for the entire lunar night.

4. Transmitted Power

Power could be beamed to the moonbase in the form of an electromagnetic wave. Beamed power has been investigated in some detail for other applications, including satellite solar power systems (SSPS) [22]. The main options for the beam are microwave or laser.

Electromagnetic Beams

The fundamental limit to the transmitter and receiver aperture sizes is set by the diffraction limit,

$$r_r r_t = 0.61 \, d \, \lambda \tag{1}$$

where r_r is the aperture radius of the receiver, r_t the aperture radius of the transmitter, d the source to receiver distance, and λ the wavelength.

For a microwave beam, aperture size is the antenna radius; for a laser, it is the radius of the lens or reflector used to focus the beam. (The receiver radius is here defined as the first zero in the diffraction pattern; this contains 84% of the beam energy. If a larger fraction of the transmitted energy is to be captured, the receiver aperture must be larger than this value.) The minimum total area is when the transmitter and receiver are of equal size, and the area is proportional to the square of the wavelength used. Thus, it is important to use the shortest practical

wavelength (i.e., the highest practical frequency).

The power efficiency of a microwave beamed system is projected to be very good, both as the transmitter and at the receiver; typically over 85% can be expected, with efficiencies above 90% not unreasonable. Unlike laser systems, an additional receiving rectenna is required on the surface. A difficulty of microwave systems is that to form narrow beams the antennas need to be large due to diffraction effects. However, a microwave antenna can in principle be made from a very light metal mesh. Microwave transmission at 2.5 GHz (λ =10 cm) has been demonstrated. 30 GHz (λ = 1 cm) has been identified as a target frequency for transmission. Shorter wavelengths yet would be desirable.

Laser transmission is an attractive option because optical wavelengths are considerably shorter than microwave wavelengths, which reduces diffraction effects and allows narrower beam spread and consequently much smaller apertures. If the laser wavelength is selected properly, the receiver can be the same solar array used to provide daytime power. Laser power transmission is discussed by de Young et al., [23]. A difficulty is that the power efficiency of conventional lasers is typically not very high, e.g., about 10% for a Kr-F excimer laser. Free-electron lasers have potentially efficiencies as high as 65% [24] as well as high power and a wavelength range down to $\leq 0.2\mu$, but are extremely massive, too massive to be used except for a surface-based system. De Young et al. recommended development of large arrays of diode lasers for power transmission. Since the maximum power of each individual diode laser is typically about one watt, an array consisting of a very large number of individual lasers would have to be used. Arrays of diode lasers have recently demonstrated power densities as high as 50 W/cm^2 with total energy efficiency of 40% [25].

An attractive alternative is the possibility of a laser directly powered by solar energy, which increases the effective efficiency by eliminating the intermediate step of conversion of solar energy into electricity [26].

The efficiency of conversion at the receiver is also not nearly as high as microwave conversion. The best solar cells can be expected to convert about 50% of the incident light into electricity at the optimum wavelength (energy just higher than the bandgap). For photovoltaic receivers the efficiency drops to zero for wavelengths much longer than the optimum. For wavelengths shorter than the optimum, the expected efficiency E is roughly

$$E = \eta_{(optimum)} \left(\lambda_{laser} / \lambda_{cutoff} \right) \qquad (2)$$

where $\eta_{(optimum)}$ is about 50% for the best cells, and λ_{cutoff} is determined by the bandgap of the solar cell material.

$$\lambda_{cutoff}(\mu) = 2.24/E_g \qquad (3)$$

Thus, as long as all of the transmitted power falls on the receiving array, the solar cell material is preferably tailored to the laser wavelength, or vice versa. However, if the spot size is larger than the receiving array, it is optimal to decrease the wavelength to put more of the power on the

array. This can be from seen comparing equation (1) and equation (2). The beam area is proportional to r_s^2, and so the fraction of the beam which is intercepted by the array increases as λ^2, while the efficiency only decreases proportionately to λ.

Transmitted Power from Space

A question of considerable importance to beamed power systems is the best location for the primary (transmitter) station.

Placing the primary power station in low lunar orbit (LLO) minimizes transmission distance. Low-lunar orbits tend to be unstable for periods of more than about 100 days; this means that the orbit will have to be actively maintained.

If a single primary power satellite is used, it will be in line-of-sight to the base for no more than half of the orbit. A LLO satellite will also be in the lunar shadow for a considerable fraction of its orbit. For a 1000 km orbital altitude, the orbital period is roughly four hours. Thus, several hours of energy storage will still be required at the base. Since providing several hours of storage when the satellite is on the other side of the moon is considerably easier than providing 354 hours of storage for the entire lunar night, this is still a major improvement.

Alternatively, at least three primary power satellites are required if one is to be in line of sight of the base at any given time.

Placing the primary power satellite at libration point L-1 (between Earth and Moon) requires transmission of power over a longer distance. The advantage is that only one satellite is needed, since L-1 is always in sight from near side of moon. The orbit is unstable for periods greater than about 50 days, but the corrections needed are small if the location is not allowed to drift very far from the equilibrium point. Occasional eclipses by the moon and the Earth will interrupt power for brief periods.

Placing the primary power station on the lunar surface, at a location on the far side of the moon preferably exactly 180° away from the base, requires the use of one or more relay satellites to transmit the power. This allows a single photovoltaic array to be used, fixed on the surface. The requirement for relay satellites means that this arrangement is unlikely to be more efficient than producing the power directly at the satellites.

An alternative to beaming power would be to transmit the power across the surface of the moon on a physical link from the second solar array on far side of moon. This would require roughly 5500 km of power lines; about distance from NY to San Francisco. While the link could be a conventional high-voltage lines, possibly made from locally-available aluminum or calcium, resistance losses would be high unless extremely high voltages were used or very large diameter wire was used. (For example, at 0.1 cm^2 cross section and 100 kV, the resistance losses for a 100 kW system are about 20%, and the mass of wire required is about 600,000 kg). If two ground power stations were used, each located 90° in longitude from the base, the transmission distance would be halved and the wire mass proportionately decreased. The required transmission line length could be greatly reduced if the base is not located at the equator. For example, if the base is located at 60°N and the transmission lines run

across the north pole, the total length can be reduced by a factor of three.

This has an additional advantage that the lines could probably be "tapped" at points along the length to run remote experiments, as well as to serve as charging stations for electrically powered exploration vehicles.

Use of superconductors for the lines would eliminate the resistance losses and allow lower wire cross section. These will need to be kept cool; this could be done by shielding them from the ground and from direct sunlight (also possibly from reflected light from the Earth).

Alternatively, the link could be fiber-optic light-guides (made from locally available silica) which direct a laser beam.

In any case, this option is likely only for an advanced moonbase.

Beamed Power from Earth

Finally, power could be beamed directly from stations on the Earth. The advantage of this is that electric power is cheap on Earth (~5¢/kW-hr), and there is no need to loft a large solar array or power beaming equipment into cislunar space. For the following example I will assume power transmission by laser.

Consider a baseline system with a wavelength $\lambda = 1\mu = 1.10^{-6}$ m. This is the approximate wavelength range for a Nd:YAG laser (1.06 μ), or a GaAs laser diode array, and is near the optimum wavelength for conversion for a Si solar cell. d(Earth-Moon) is $3.8 \cdot 10^8$ m, and the lens diameter is 2 meters. A two meter diameter lens (or mirror) is very large by telescope standards (for example, the Hubble Space Telescope is a 2.4 meter diameter mirror). However, the lens need not be telescope quality. The lens could be a fresnel lens, or, since it need only function at a single wavelength, a holographic optical element.

For diffraction limited beam spread, the spot size is 230 meters; the illuminated area 170,000 m². For the array specified at 100 kw and a solar conversion efficiency of 18.5% efficiency, the array area is 400 m², and so the array intercepts only 0.25% of the beamed power. The required beam power would be 85 MW.

This can be reduced by decreasing the laser wavelength to 0.5μ and increasing the solar cell bandgap from 1.1eV (Si), to 2.0 eV (GaAlAs alloy). This is about the widest bandgap that will still give good solar conversion efficiency for daytime power (also, wavelengths below about 0.3μ begin to be significantly absorbed in the atmosphere.) The array is then oversized by a factor of two over the size required for daytime power, and stationary reflectors are used to intercept an additional factor of 4. Since the Earth is nearly stationary in the Lunar sky, these reflectors do not require tracking, and need be no more than thin reflective sheets of plastic. The array will now intercept 8% of the beam. If 50% power at night is now assumed, the required beam power is 2.2 MW. Further reductions in power could be achieved by the use of a larger area of thin reflectors, as discussed in the next section.

Note that the total system requires twice as many lasers as are actually in use, since at any given time half will be on the wrong side of the Earth. Such a system would utilize many lasers from different sites--presumably desert areas and mountaintops--so that laser failure will not interrupt

power. The required 4.4 MW could be provided, for example, by 56 eighty-kw lasers (twenty-eight of which are running at any given time). Such power levels are high compared to those achieved by current technology CW visible light lasers, but in the range likely to be reasonably achievable for future high-power lasers. It is many orders of magnitude higher power than currently achieved by diode lasers. Problems of tracking, reliability, and atmospheric turbulence remain to be addressed. The intensity of the beam at the site is considerably less than solar intensity, and thus would not present a hazard to base personnel unless they look directly into the beam. This hazard could be removed if the solar array is located in an area which is kept off limits to astronauts during the night, or if the suit visors and the windows of the base are designed to incorporate a rejection filter at the proper wavelength.

5. Innovative Concepts

Solettas

One proposal has been to use "Solettas", or orbital mirrors, to reflect sunlight to the surface solar panels [27]. The fundamental limit to soletta illumination is the minimum spot size d_s at the receiving array. This is fixed by the angular diameter of the sun and the orbital altitude:

$$d_s = h\alpha + d_m \qquad (4)$$

where h is the slant range between the orbiting mirror and the ground spot, α is the angular diameter of the sun (about .01 radian), and d_m is the mirror diameter. The spot size can be decreased by lowering the orbital altitude, but this means that the fraction of time that any particular mirror can view the receiving array also decreases, thus increasing the required number of mirrors in orbit. When the mirror size d_m is less than $h\alpha$, the illuminated spot size is constant and the illumination intensity decreases with mirror area. Except for very large systems, the spot size is much larger than the solar array, and thus the array intercepts only a small fraction of the energy reflected by the mirror. The mirror size needed is thus independent of the array size. Consequently, the concept is most suited for very large power requirements.

An initial design discussed by Criswell [27], as shown in figure 1, is calculated for 800 kW of night power. Four mirrors are assumed, each 40 km² in area. The illumination level is 11% of the daytime illumination. The mirrors were assumed to be fabricated from light-weight solar-sail technology, with a total mass of 1 million kilograms.

Finally, it should be noted that the soletta concept requires exceptionally good mirror surface accuracy and pointing accuracy at comparatively high slew rates. A quarter degree of pointing error will result in the illuminated spot missing the surface array; a similar amount of ripple in the surface will defocus the spot. These surface and pointing tolerances are considerably higher than those needed for solar sail technologies.

Conversion of Earthlight

The Earth is nearly fixed in the lunar sky. This raises the intriguing possibility of utilizing the solar array to convert sunlight reflected from the Earth [28].

The albedo of the Earth is 0.36 (±.06, depending on cloud cover). Even when full, the Earth is 10,000 times less bright than the sun. At half phase, which is the worst case for a base located at the center of the near side of the moon, the Earth is 20,000 times less bright than the sun. Therefore, to produce full power at sunset and sunrise, a solar array would have to be 20,000 times larger than the one required for daytime power. If 30% power is acceptable as the nighttime average, the array need be only 4,000 times larger than the daytime array.

This could conceivably be done using mirror concentrators. A minimum mirror need be no more than a flat sheet of very thin reflective plastic. One micron thick aluminized Kapton has a mass of 1.4 gr/m^2, 600 times lighter per unit area than the 300 W/kg solar array assumed. Thus, a minimum mass 4000x concentrator could weigh as little as about 7 times the mass of the solar array itself. This is still a considerable problem: the system would require 4,000 sheets of Kapton, each one carefully aligned, for each panel of the array. The mass does not include the additional area required for cosine theta loss and reflectance losses, and additional mass for the structure to support it. Also, the array will likely also require tracking: the Earth doesn't move much, but it does move some. In short, this solution is unlikely to be practical.

Lunar Polar Base

It is possible that locating a lunar facility at one of the poles of the moon could alleviate the problem of the lunar night, since the axis tilt of the moon is so low that placing the arrays on a relatively short tower (or conveniently placed mountain) could allow them to be constantly illuminated [29,30]. This is shown in schematic in figure 2.

A problem with the polar location for a lunar base is that, like the Earth, the polar regions of the moon are subject to six months of darkness during the hemisphere's "winter". This could make exploration and work outside very difficult. Even during the "summer," the sun angle remains very low (within 1.5° of the horizon). This means that inky black shadows will cover almost all of the surface, making exploration (and even walking around!) very tricky.

Sun-following Moonbase

In the sun-following moonbase concept, the lunar base constantly moves around the moon to stay continually in sun [31]. The rotational velocity at the lunar equator is 16.6 km/hr (10 MPH). If the moonbase is sited 60° N, where the local sun angle is a comfortable 30° off horizon, the required average velocity is only 8.3 km/hr (5 MPH); and even less if the path chosen is across the pole. Actual moonbase speed will be 10 MPH during 12-hr "drive" shift and 0 MPH during 12-hr "work" shift. Figure 3 shows a version of such a mobile moonbase using design concepts familiar from other space habitat structures.

Conceptually this is an extreme solution to a simple problem, but as well as providing continual solar power, it does have other advantages: it

eliminates the 354-hr dark period when outside exploration is difficult or impossible, thus effectively doubling the working hours of the staff; and the base is not "stuck" in one spot, but continually samples new territory.

The path should be maintained near the sunrise terminator, to give as close to 14 day of "slack" as possible for repairs. Since the moonbase would consist of many independently mobile modules, no single failure would be critical. Any one unit could be evacuated if necessary and repaired on the next cycle.

An alternative version would be to have two separate lunar bases on opposite sides of the moon, with the crew transferred from one to the other on a two-week cycle. This has the disadvantage that the entire moonbase must be doubled.

6. Conclusions

A constant supply of electrical power is important to human occupancy on the moon, and one such supply is solar energy. The major difficulty in a solar-powered moonbase consists in providing steady power over the long and dark lunar night. At the moment, the promising solution for a near-term moonbase appears to be the use of regenerative fuel-cells with cryogenic storage, a technology which is not yet fully developed but is unlikely to have any fundamental technical difficulties in development. Nevertheless, a wide variety of other concepts for solar night power have been proposed, which are summarized in table 1. Not all have been examined in depth. All have some apparent drawbacks; many will only be useful for a large, "evolved" moonbase.

There is certainly room yet for clever new ideas.

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Table 1

Approaches to solar power for the lunar night

Storage Options

method	*Specific Power (W-hr/kg)*	
	present	*anticipated*

Electrical Storage

Batteries	32	150
Fuel Cells	50	1500
Capacitors	10	20
Inductors	0.5	100

Physical Storage

Compressed Gas		*(impractical)*
Thermal storage	-	250*
Lunar thermal storage		10000†
Flywheel Storage	20	35
Gravity Storage	-	<1

*heat
†heat. *Will depend on insulation requirement*

Continuous Power Concepts

method	*comments*

Transmitted Power

Microwave beam	*Primary station in LLO or at L-1*
Laser beam	*Primary station in LLO or at L-1*
Transmission lines	*Primary station on Lunar farside*
Ground-based laser	*Primary station on Earth*

Innovative Concepts

Soletta	*Orbital mirrors; practical only for large systems*
Earthlight Conversion	*Requires very large collectors*
Lunar Polar Base	*Low sun angle at base*
Sun-Following Moonbase	*Not at fixed location*
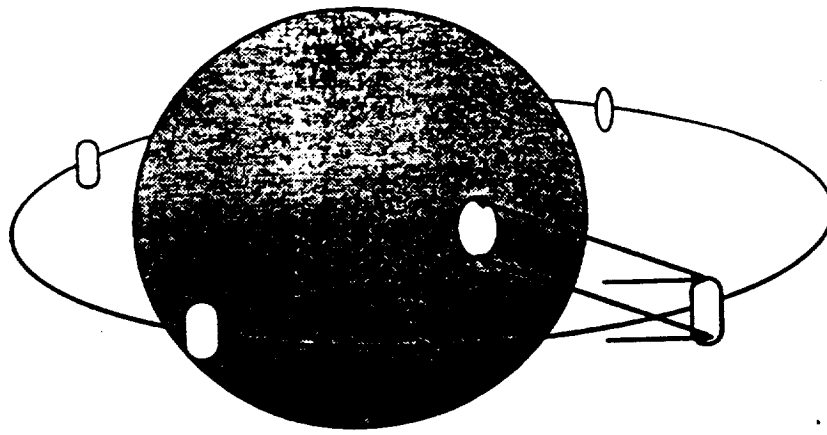
Figure 1: the "Soletta" solution:

Four mirrors in high-inclination, low altitude orbit
provide 10% of one sun illumination to solar arrays
orbital altitude = 500 km periapsis, 1050 km apoapsis
8.7 km diameter mirrors at 6 grams/sq. m
240 tons each; 1000 tons total
minimum spot size 34 km
illuminated area 1000 square kilometers

Detail
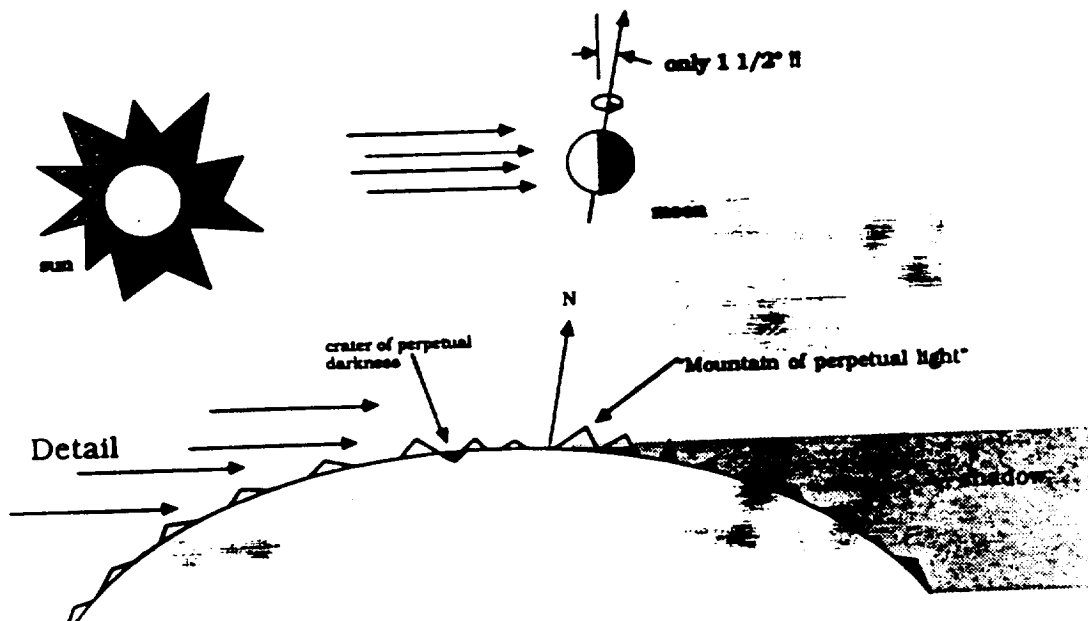
Figure 2. Lunar Polar Base (Schematic)

by placing the solar array atop a high enough mountaintop close to
the lunar pole, it will always be in sunlight!
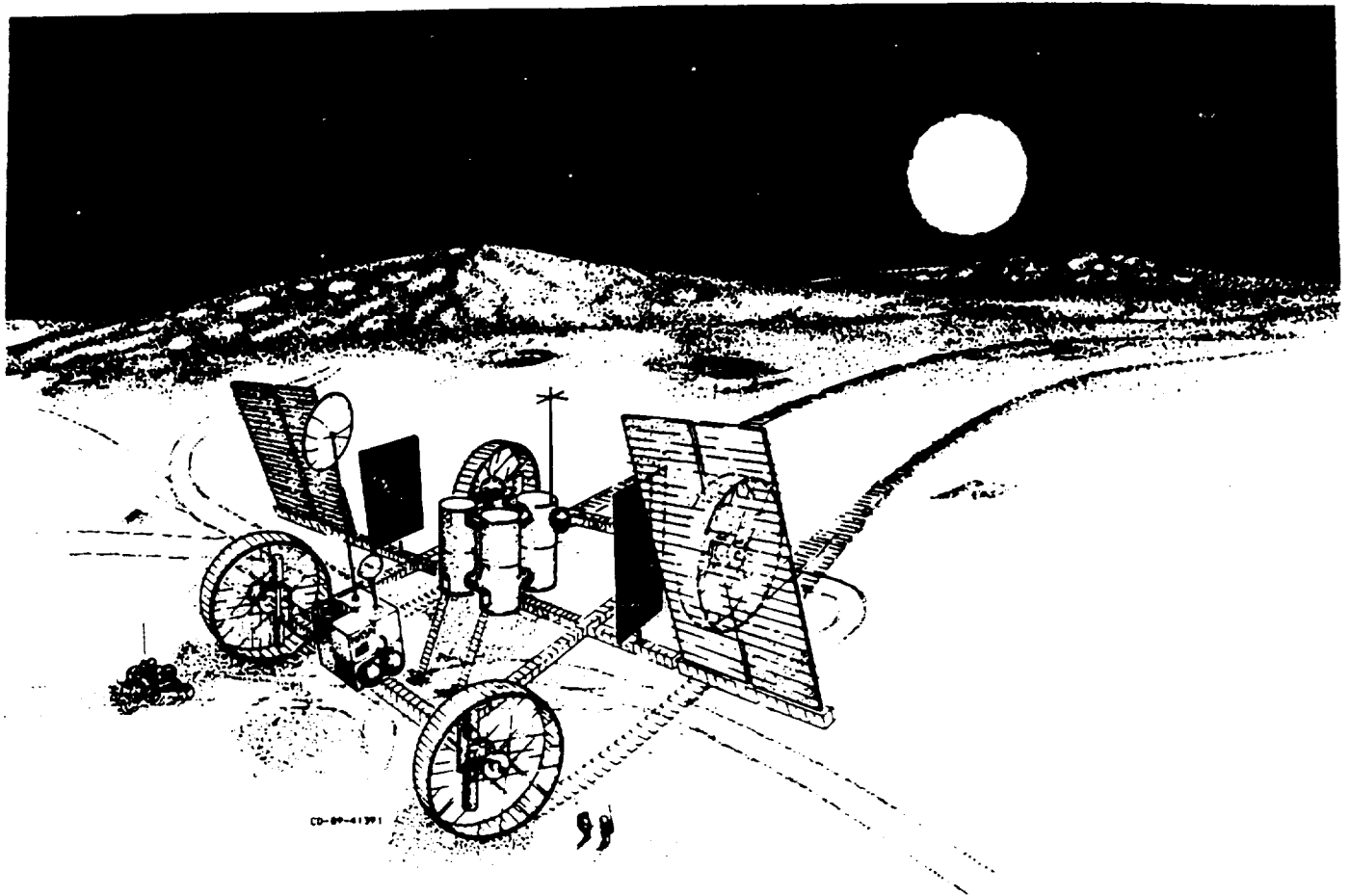
Figure 3: Sun-following moonbase
moonbase moves continuously around the moon
to stay in sunlight
moonbase speed:
10 MPH during 12-hr "drive" shift
0 MPH during 12-hr "work" shift

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15. Supplementary Notes

16. Abstract

Providing power over the 354 hour lunar night provides a considerable challenge to solar power concepts for a moonbase. The paper reviews concepts for providing night power for a solar powered moonbase. The categories of solutions considered are electrical storage, physical storage, transmitted power, and "innovative concepts". Electrical storage is the most well-developed option. Less developed electrical storage options are capacitors and superconducting inductors. Physical storage options include storage of potential energy and storage of energy in flywheels. Thermal storage has potentially high energy/weight, but problems of conduction and radiation losses during the night need to be addressed. Transmitted power considers use of microwave or laser beams to transmit power either from orbit or directly from the Earth. Finally, innovative concepts proposed include reflecting light from orbital mirrors, locating the moonbase at a lunar pole, converting reflected Earthlight, or moving the moonbase to follow the sun.

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Satellite Eclipse Power by Laser Illumination

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ABSTRACT

A method is proposed to eliminate the energy storage system required to power satellite in geosynchronous orbit during eclipse. An array of high-power CW lasers is situated at one or more ground locations in line of sight of the satellite, preferably on mountaintops. The lasers are provided with a tracking system, and lenses or mirrors of sufficient size to reduce the beam spread due to diffraction. As the satellite enters eclipse, the laser arrays illuminate the solar arrays on the satellite to a level sufficient to provide operating power.

INTRODUCTION

Geosynchronous Earth orbit (GEO) satellites are a valuable portion of commercial space activities. All satellites now operating in GEO are powered by solar arrays. For operation during eclipse periods, when the Earth shadows the satellite from the sun, battery back-up system charged by the solar array provides power.

The geosynchronous orbit is in eclipse for only a short period of time around the equinoxes, typically about 90 days total per year. Eclipse duration is maximum at the equinox, when it reaches just under 70 minutes, or about 5 percent of the orbit.

On a typical communications satellite, about 1/5 of the total satellite mass is the power system [1]. For a 5kW power system, the power system total mass is roughly 900 k [2]. The energy storage system, for current nickel-hydrogen batteries used in GEO

comprises 42% of the power system weight. An additional 37% of the power system mass is electrical power conditioning, a significant portion of which is needed for battery charge regulation. Only 21% of the power system mass is actually the solar array, and about 10% of the array area is dedicated to recharging the batteries. It is remarkable that over half of the mass of the power system has no other function than to provide power for less than one percent of the operating time. Eliminating the requirement for an energy storage system could reduce satellite mass by 10%.

In this paper a method of eliminating the storage system is discussed, where the satellite is illuminated during eclipse by a ground-based laser.

The proposed system is simple. An array of high power continuous-wave (CW) lasers is situated at one or more ground locations in line of sight of the satellite, preferably on mountaintops. The lasers are provided with a tracking system, and lenses (or mirrors) of sufficient size to reduce the beam spread due to diffraction. As the satellite enters eclipse, the laser arrays illuminate the solar panels on the satellite to a level sufficient to provide operating power.

No added elements are needed for the satellite. The solar array needed to receive the beamed power is already in place on the satellite. Laser power is required only for periods of less than 70 minutes per day for 90 days out of the year. This allows ample time for laser refurbishment and preventative maintenance. The fact that the laser is on the Earth allows considerable design simplification; unlike in-space systems, where any failure is fatal, terrestrial systems can be easily repaired, so highly redundant systems are not required. Since one of the failure modes of a satellite is battery failure, by eliminating the battery the mean time to failure, and hence the expected life, of the satellite can be increased.

Each ground laser station can successively illuminate several satellites at different longitudes (see figure 1). As one satellite exits the eclipse region, the laser is retargetted to another satellite entering the eclipse. If the laser could scan angles down to the horizon, ten satellites could be successively illuminated. Even if a ground-based laser can scan only an angle of ±45° from the zenith, a single laser station could provide power for five satellites at different longitudes.

Solar cells in GEO are subject to degradation in power due to trapped radiation and solar flares. Solar arrays are typically oversized in order to provide power under worst-case end of life conditions. Once set up to provide eclipse power, the laser power system described could also be used to provide supplementary power if needed to compensate for radiation damage to the arrays.

With some exceptions [3-6] most discussions of power transmission in space focus on microwave transmission. Laser transmission was chosen over microwave for several reasons. First, optical wavelengths are considerably shorter than microwave wavelengths, which reduces diffraction and so allows a much narrower beam. Consequently, the receiver and the transmitter (i.e., the photovoltaic cells and the laser

K-3

can be considerably smaller for laser transmission. Secondly, if the laser wavelength is selected properly, the receiver can be the same solar array used to provide normal power. An additional microwave rectenna is not required on the satellite.

PHOTOVOLTAIC RECEIVER

The best photovoltaic cells can be expected to convert about 50% of monochromatic incident light at the optimum wavelength into electricity. The efficiency drops to zero for wavelengths much longer than the optimum. For wavelengths shorter than the optimum, the conversion efficiency for monochromatic light η_{laser} is approximately:

$$\eta_{laser} \approx \eta_{(optimum)} (\lambda_{laser} / \lambda_{cutoff})$$ (1)

λ_{cutoff} is theoretically determined by the bandgap of the solar cell material:

$$\lambda_{cutoff} = 1240/E_g$$ (2)

for λ_{cutoff} in nanometers (nm), where E_g is the bandgap of the semiconductor material in electron volts. In the real world, solar cells do not perform optimally for photon energy out to the bandgap, since light near the bandgap is only weakly absorbed. For example, single crystal silicon has a bandgap wavelength of about 1100 nm; however, the peak of the spectral response is typically near 950 nm for the solar cells used on existing spacecraft. The efficiency drops rapidly toward zero at longer wavelengths. At 1060 nm, a wavelength of interest for lasers, the efficiency is down by a factor of three more from the peak. Figure 2 shows a measured spectral response of a conventional silicon solar cell of the type similar to those used for spacecraft applications [7]. The response is quite linear out to about 950 nm, but drops off rapidly above this value. However, it is possible to design solar cells to increase the long-wavelength performance, using techniques such as light-trapping [8].

For cells near the optimum bandgap for solar conversion, such as GaAs, the monochromatic light efficiency η(optimum) can be roughly estimated as double the conversion efficiency for sunlight. The best GaAs solar cells are slightly under 24% efficient for the solar spectrum, and thus can be expected to be about 50% efficient at the optimum wavelength.

The minimum spot radius of a transmitted laser beam is set by the diffraction limit,

$$r_{spot} = 0.61 \, d \, \lambda / r_{lens}$$ (3)

where r_{lens} is the radius of the lens or reflector used to focus the beam, d the source to receiver distance, and λ the wavelength. The spot radius is here defined as the first zero in the diffraction pattern; this contains 84% of the beam energy. As discussed below, the diffractive limit can only be achieved if adaptive optics are used to eliminate

K-4

atmospheric beam spread.

If the spot size is smaller than the receiving array, the laser wavelength is preferably the chosen at the optimum value for the solar cell performance. However, if the diffraction-limited spot size is larger than the receiving array, it is desirable to decrease the wavelength to put more of the power on the array, even at the price of decreasing the efficiency. Since efficiency only decreases proportionately to λ, while the illuminated area is proportional to the spot radius squared (if atmospheric beam spread is eliminated), it is desirable to use the shortest practical wavelength. The opacity of the atmosphere to short-wavelength ultraviolet places a lower limit to the wavelength at about 350 nm.

OPTICS

A key element in achieving small spot sizes is the use of a large optical aperture on the ground system. For optimal systems, the lens size should be in the scale of meters. While it may be argued that meter-scale optics are expensive (for example, the Hubble Space Telescope is a 2.4 meter diameter mirror), it must be kept in mind that the optics do not have to be of telescope quality, and need only operate at a single wavelength. The optics may be fresnel lenses or holographic optical elements, which may be very cheaply manufactured. Other programs, such as the U.S. SDIO research effort, have concluded that manufacturing 4-8 meter mirror elements will not be a major difficulty.

In the real world, pointing accuracy and atmospheric turbulence degrade the effective spot size. Achievable pointing accuracy is high enough that this is not a limiting factor. Atmospheric turbulence limits the resolution limit of astronomical telescopes to slightly less than 1 second of arc, or about 4 microradians, increasing slightly at shorter wavelengths. At the distance of GEO, $3.5 \cdot 10^7$ m, this contributes about 135 m to the spot diameter.

The effect of turbulence is greatly reduced by operating the laser from the highest possible altitude, such as a mountain peak, to decrease the optical path through the atmosphere. An alternate possibility is to operate the lasers from airborne locations such as high-altitude aircraft or balloons. Since the lasers need only be operated for periods of roughly an hour, this may be feasible, although the laser power source and the increased difficulty of pointing stability could provide significant constraints.

Better performance can be achieved by using techniques which compensate for atmospheric distortion [9]. One such technique is the flexible mirror telescope, where the mirror pointing and shape is continuously adjusted to compensate for distortions in the shape of the wavefront due to turbulence. The 1.2 m telescopes at the U.S. Air Force Maui Optical Station, located on Mt. Haleakala at 3 km altitude, resolve objects in orbit to a resolution of 0.4 microradians [10]. This resolution would contribute about

13 m to the spot diameter in GEO. An alternate technique is to use an active phased array, or phase conjugate mirror. In this case a pilot beam would be beamed downward from the spacecraft to the phase conjugation system, which would synthesize a beam precisely opposite in phase and direction to the pilot beam. This would then be retrodirected to the satellite with the atmospheric distortion corrected.

Weather effects place another constraint on the operation of the system. Optimally, the laser ground stations should be placed on the peaks of mountains which are above most clouds. To minimize the effect of unfavorable conditions at any one location, the lasers could be placed at widely separated locations. Use of seven isolated locations will result in over 99.9% beam availability [9].

LASERS

Lasers to be considered must operate in the wavelength range centered around the visible spectrum in which the atmosphere is nearly transparent. The minimum wavelength is about 350 nm, limited by atmospheric absorption by ozone [9]. The maximum wavelength to be considered is 1100 nm, unless new photovoltaic receivers responsive to long wavelength light are to be developed.

The highest power lasers currently available use carbon dioxide (CO_2) as the lasing medium. While CW power levels of over a megawatt have been demonstrated, the wavelength of 10600 nm is far too long to be considered. If future satellites use a thermal, rather than photovoltaic, energy conversion system, however, use of CO_2 lasers may be an option.

Of currently developed laser technologies, the best high-power CW lasers are Neodymium doped Yttrium-Aluminum Garnet (Nd:YAG). The wavelength of 1064 nanometers is theoretically near the optimum energy for conversion by a silicon solar cell, however, in practice, solar cells are optimized for shorter wavelengths and do not have very high efficiency at 1064 nm. Further, the long wavelength response degrade rapidly in a radiation environment, and thus Nd:YAG illumination would result in decreasing power at the satellite end of life. Frequency doubling the Nd:YAG to 530 nm results in a considerably better wavelength, however, frequency doubling will reduce both the laser efficiency and the laser power by roughly a factor of two.

The best currently available Nd:YAG lasers have averaged CW power of 1 kW [11].

Argon ion lasers, with primary emission lines at 514 and 488 nm, are also at a good wavelength, but have extremely low electrical to light conversion efficiencies.

An alternative currently being developed is the solid state diode laser. The highest power GaAs diode lasers operate at about 795-820 nm, which is nearly optimal for existing silicon solar cells. Shorter wavelength GaAlAs lasers can be manufactured which would be preferred for GaAs solar cells. An array consisting of a very large number of individual lasers could yield the required power. Monolithic arrays of diode

lasers have recently demonstrated power densities as high as 80 W/cm^2 and CW power levels of one kW [12]. The problem of beam-combination from a large number of individual diode beams is a technological problem which still must be solved. The current cost of commerical high-power diode laser arrays [13] is about $400 per output watt, however, it is expected that the price will decrease as the production increases. Costs as low as $1/watt have been suggested as achievable with future diode laser arrays, assuming high volume production.

Excimer lasers are available with very short wavelengths. 750 W Xenon Chloride (XeCl) excimer lasers have been manufactured by Lambda Physik [14], with a laser wavelength in the UV at about 308 nm. Another alternative, XeF, lases at 351 nm. Other excimer laser gasses are typically below the wavelength range of atmospheric transparency, although it is important to note that 1 MW KrF laser design is discussed by De Young *et al.* [4] and others [15] operating at 248 nm.

For a more advanced system, the free-electron laser (FEL) is a very attractive choice. A FEL has potentially very high efficiency as well as high power [16] and is, in principle, tunable over a wide range of wavelengths, down to as low as <200 nm. Free electron lasers have been proposed in the multi-megawatt power range; for example, Boeing Corporation has contracted to design a multimegawatt FEL to be built at White Sands for defense research. Existing FELs built for defense research are commonly quoted as operating in the "multi-kilowatt" power range. A FEL operating at wavelengths as low as 600 nm has recently been demonstrated [17]. A disadvantage is that the systems are likely to be heavy, and are not yet demonstrated at the wavelengths of interest.

Finally, the energy efficiency of the laser is an issue, although not the major criterion for selection. While many lasers have low conversion efficiency, power is extremely cheap on Earth compared to the cost of power in space. High efficiency is the primary feature of semiconductor diode lasers. Existing high-power lasers have relatively low efficiency, since the conversion from electrical power to laser power typically requires an intermediate step, *e.g.*, a flashlamp. The best flashlamp-pumped Nd:YAG lasers [11] have an efficiency (electrical input to laser output) of about 6%. Diode-pumped Nd:YAG lasers have roughly double this efficiency. The power efficiency of excimer lasers is typically about 10%, *e.g.*, for existing Kr-F excimer laser. Lasers being developed have considerably higher efficiency. Available high power diode laser arrays [13] have a total energy efficiency of 40%; a 70% efficiency has been obtained in the laboratory [4,6]. Efficiencies as high as 84% are possible. Free electron lasers also have quite high efficiencies, with efficiency is expected to be as high as 65% [15].

Alternative discussions of lasers for space power transmission applications, focussed on space-based systems using advanced technology lasers and PV receivers, can be found in studies by NASA Langley Research Center, cited in references [4] to [6].

BASELINE SYSTEM

Consider a baseline system with a wavelength λ near one micron, or 1000 nm ($1 \cdot 10$ m). This is the wavelength range for a Nd:YAG laser, and close to that of a GaAs laser diode array. It is slightly longer than the optimum conversion wavelength for a Si solar cell. The distance d(surface-GEO) is $3.5 \cdot 10^7$ m, and the lens diameter is 2 meters. For diffraction limited beam spread, the diffraction-limited spot radius at GEO is 23 meters. This is sufficiently small that the beam spread at the array is almost entirely due to atmospheric turbulence. The turbulance-limited spot size is about 15,000 m^2.

For 10 kw of baseline power with a solar array efficiency of 18.5%, the array area 40 m^2, and so the array intercepts only about 0.25% of the beamed power. The required beam power would be 8.5 MW.

It is reasonable to expect that use of adaptive optics could reduce the atmospheric beam spread by a factor of ten. The spot size is now limited by diffraction. If the laser wavelength is then reduced by a factor of two to ~500 nm, the total spot radius at GEO is 13 m. The illuminated area is 560 m^2, and the array now intercepts 7% of the incident power. The net result is that the laser power needed is ~500 kW.

The required 500 kW could be provided, for example, by twenty-five 20-kw laser units, to allow any single unit to be taken off line without system failure. Such power levels are high compared to those achieved by current technology CW visible light lasers, but in the range likely to be reasonably achievable for future high-power lasers. It is many orders of magnitude higher power than currently achieved by diode laser. Problems of t█████ng and reliability remain to be addressed.

CONCLUSIONS

Illumination of a satellite in geosynchronous Earth orbit at levels sufficient to provide full spacecraft power should be feasible with arrays of lasers using technology likely be available in the near-term. The primary limitation at the moment is beam spread due to atmospheric distorions; this could be reduced by the use of adaptive optics compensate for atmospheric turbulance.

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Figures

Figure 1. A single ground station can illuminate several satellites in GEO in sucession as each or enters the Earth's shadow.

Figure 2. Measured output of a standard silicon solar cell as a function of incident wavelength. The dashed line indicates the ideal (unity quantum efficiency) spectral response.
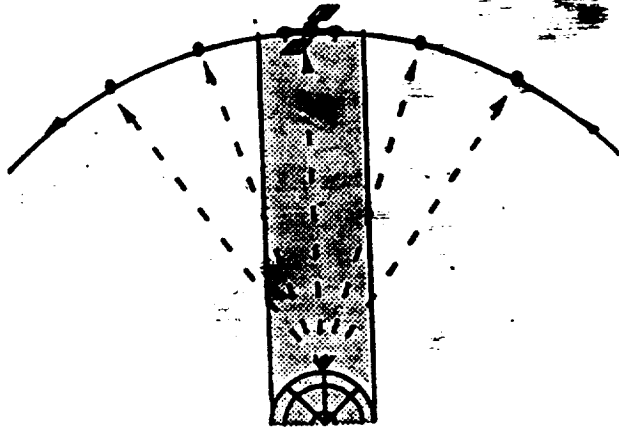

Figure 1. A single ground station can illuminate several satellites in GEO in sucession as each one enters the Earth's shadow.
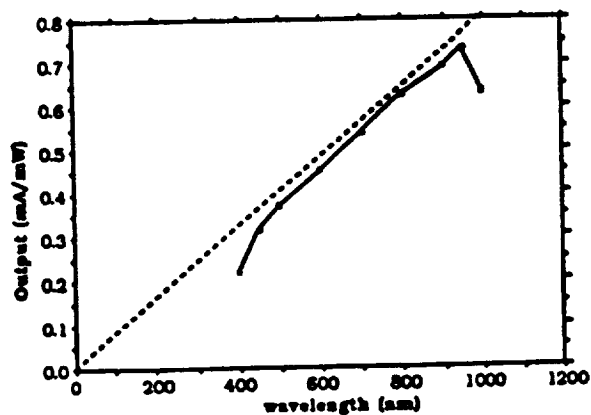

Figure 2. Measured output of a standard silicon solar cell as a function of incident wavelength. The dashed line indicates the ideal (unity quantum efficiency) spectral response.

Power Beaming

LASER PHOTOVOLTAIC
RECEIVER CELL DEVELOPMENT

presented by

E. P. Coomes, Manager

Space Power and Propulsion
Pacific Northwest Laboratory

to

TECHNOLOGY WORKSHOP
ON BEAMED POWER

NASA Lewis Research Center, Cleveland, Ohio
February 5, 1991

Pacific Northwest Laboratory

SPGD (Space Power Generation and Distribution)

Agenda

- Concept Description
- Lunar/Mars Application
- Research Activities at PNL
- Transmission System and Issues
- General Discussion

What is SPGD?

Space Power Generation and Distribution (SPGD)

- Central power generation satellites transmitting power to remote users satellites

- Parallels terresterial central power generation plants transmitting power to remote users over power lines

- Space transmission lines are energy beams

- Based on existing and newly emerging technologies from SDI and NASA

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What is Power Beaming?
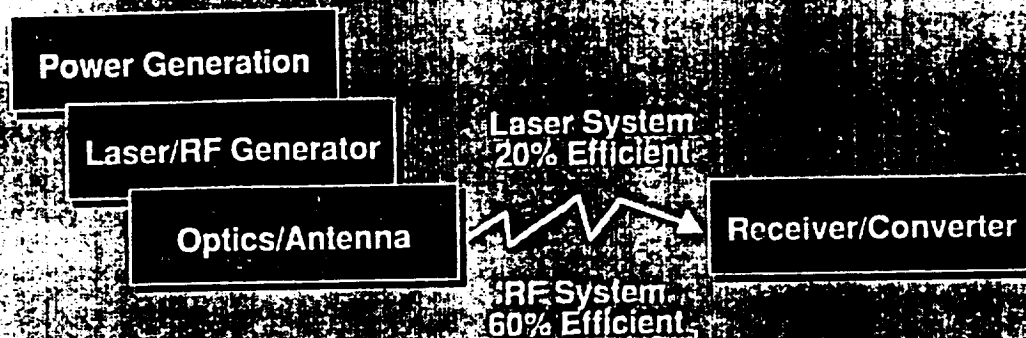
Conventional Power Approach

Power Source	System

Power Beaming Approach

Power Source	Transmitter

Receiver	System
Receiver	System
Receiver	System

Power beaming is the approach to space power generation and distribution (SPGD) that separates the power source from end-use application and links them either by laser or RF energy beams. There are three basic approaches to power beaming: SPACE TO SPACE; SPACE TO SURFACE; and SURFACE TO SPACE. While all these are applicable to Earth systems, only the first two approaches are viable for SEI applications.

DESCRIPTION
A power beaming system consists of four major subsystems: a prime power source, an energy beam generator, a transmission aperture, and an energy beam receiver / converter. A laser based system uses AlGaAs laser diodes operating at 50% efficiency to generate an infrared laser beam at .83 microns. For a transmission range of 37,000 km 7.5 meter optics are needed to form the final output beam. The laser receiver consists of GaAs based photovoltaic cells tuned to the laser frequency. Analytical models have shown monochromatic that cells with efficiencies in excess of 70% are possible. The goal is to develope a receiver array with 55% or more conversion efficiency. This would produce a system with an overall transmission efficiency of 20%. An RF transmission system consists of a microwave or millimeter wave generator operating at 90% efficiency. The output is fed to a large aperture (for a range of 37,000 kn the aperture is on the order of 300 m @ 245 GHz and 3000 m @ 2.45 GHZ) output antenna. The receiver is a dipole antenna and rectifier commonly referred to as a RECTENNA. At 2.45 GHz rectennas have demonstrated conversion efficiencies of 87%. The prime power source can be either nuclear or solar generating the necessary electric power to drive the laser or RF generator.

RECTENNAS have yet to be demonstrated at frequencies above 100 GHz and there is concern that conversion efficiency may decrease as frequency increases. The size of beam power transmit and receive apertures, either optic or RF antenna, is a direct function of the operating frequency and the transmission range. For long range transmission, RF systems will always have larger apertures than laser systems. The sizes presented here are for the same range and the transmitter and receiver apertures based on the aperture diameter product are selected so as to provide apertures of equal size. Those presented in the vu-graph are selected to provide a 2-1 ratio betweet transmitter and receive aperature.

Power Beaming

Benefits/Spin-Offs

SEI

- Commonality of systems and hardware development between surface power and space transportation
- Significantly reduced development and deployment costs
- Required IMLEO reduced therefore launch costs reduced
- Increased surface power available greatly enhances SEI mission objectives and alternatives

Terrestrial

- Laser receiver development would establish GaAs based integrated circuit industry
- Power beaming can be developed and deployed in Earth orbit providing early return on investment
- Systems and hardware developed for near Earth power beaming would directly support SEI Lunar and Mars Missions
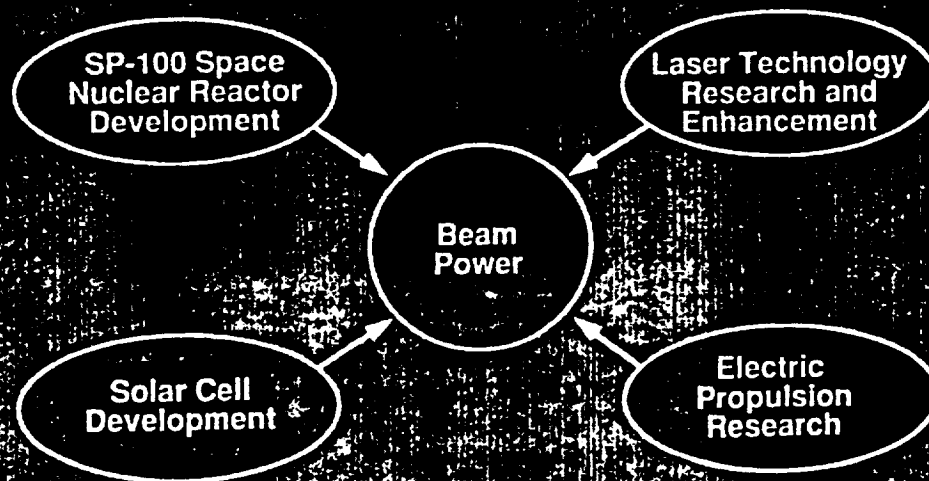
BENEFITS / SPIN-OFFS

The biggest benefit of power beaming to SEI is the commonality of systems and hardware that would exist between surface power and space transportation. Because of this commonality fewer systems must be developed and deployed, therefore, SEI system development and deployment costs are significantly reduced. Launch costs are also reduced because less mass is needed in LEO for each mission. Power beaming would also increase the amount of power that would be available on the surface. This would significantly enhance SEI mission objectives while expanding mission options and alternatives. For example, as currently envisioned the lunar mission requires nuclear power on the surface to provide the energy necessary to support lunar base development. There is no reasonable backup to nuclear on the surface. Power beaming using a nuclear power source in space could meet the same mission requirements and the backup to the nuclear power source in space a solar power source in space.

The development of power beaming would also provide significant benefit terrestrially. The development of GaAs based laser receivers would lead directly to the establishment of a GaAs based integrated circuit industry. Since GaAs IC chips operate 20% faster and at higher temperatures than silicon IC chips, any product using IC chips (computers, communications equipment, etc.) would be improved. The economic potential is tremendous. Power beaming can also be developed and deployed in earth orbit independent of SEI. This would increase the power available to satellites and systems operating near-Earth by almost an order of magnitude thus enhancing near-Earth mission capabilities. Deployment of near-Earth power beaming would provide early return on our investment in space technology. Using the power sources developed for near-Earth beam power satellites, SEI need only develop high power electric thrusters to have NEP systems available, thus, reducing the cost burden of SEI. Adding the near-Earth beam power transmitter to these NEP systems, the lunar and mars surface power requirements can be met with out the development of major new systems again reducing the cost burden of SEI.

Advantages of Power Beaming

- A commonality of power assets would exist
- Provides synergism of power system technology
  - No longer necessary to tailor each power system
  - User needs only a receiver and minimal storage
- Nuclear systems in high earth orbit increases safety
- Power availability increased by an order of magnitude
- New military and civilian mission options possible
- Power infrastructure available for space commercialization

Technology Interaction

SP-100 Space Nuclear Reactor Development

Laser Technology Research and Enhancement

Beam Power

Solar Cell Development

Electric Propulsion Research

TECHNOLOGY STATUS

The laser technology is based on SDI DEW technology developed by the PILOT program directed by the Air Force. At present AlGaAs semiconductor lasers are 34% efficient converting electricity to laser light. To support power beaming needs, these systems must reach at least 50% efficiency. Current power levels are on the order of a hundred watts and should reach thousands of watts by 2000. Power beaming will need systems with outputs in the hundreds of thousands of watts range. Pointing, tracking, target acquisition, command and control systems and technologies needed to support power beaming, laser or RF, are currently being funded through SDIO. However, budget cutbacks may result in the termination of many of these technology programs.

Receiver / converters for laser systems build on GaAs solar cell technology. By tuning these cells to the laser transmission frequency high conversion efficiencies are possible. Monochromatic GaAs cells have demonstrated cell efficiencies as high as 41%. By doping the cells with a small amount of Al, graded AlGaAs monochromatic cells have the potential of achieving greater than 70% conversion efficiency. The goal is to develop cells that will yield an array efficiency of 60%.

SPGD (Space Power Generation and Distribution)

Technology Base

Builds on Existing Programs
- Power source: SP-100, MMW
- Power transmission: SDIO - DEW
- Receivers: USAF, SDIO, NASA, SERI
- Pointing and tracking: SDIO
- Command and control: SDIO

Critical Path Technology
- SP-100 and laser transmitter
- Both could be available by early 2000's

Power Beaming Capabilities

Transmitter:

- Solid State Laser   AlGaAs
- Efficiency   50%
- Power Density 400 w/cm^2
- Operating Frequency $0.833 \text{ }\mu\text{m}$

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Power Beaming Capabilities

Receiver:

- Tuned Photovoltaic   GaAs
- Conversion Efficiency 60%
- Power Density $0.3 - 0.5 \text{ w/cm}^2$
- Specific Mass 3 kg/m^2

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CHARACTERISTICS / GOALS

For a laser beam power transmission system to be effective, an overall transmission efficiency of 20% or greater is needed. With this efficiency the remote power generator (nuclear or solar) must produce 5 watts for every watt delivered to the user. A laboratory beam power test bed using off the shelf state-of-the-art AlGaAs semiconductor laser diodes and silicon solar cells (with 13% monochromatic conversion efficiency) has achieved 3.5% overall transmission efficiency. A large scale RF system, tested at Goldstone as part of the DOE Solar Power Satellite program, demonstrated a transmission efficiency at 2.45 GHz in excess of 60% using a 75 kW transmitter.

Power beaming systems have some unique system characteristics. The specific power for surface power applications is significantly less than in-place power systems because only the receiver and power conditioning is on the surface. The transmitter is in space and the power source, if NEP was the transportation system used to deliver the system, has already been accounted for. Laser systems by virtue of their shorter wave length than RF systems will always have smaller apertures than RF for the same transmission range. Laser systems look most promising for long range transmission and RF systems appear best suited for local distribution over a few thousands of kilometers. The cost of a watt of beamed power is about half that of a watt of inplace power because the prime power source can be considered free. Power beaming combined with NEP can meet the integrated mission requirements for both planet surface power and space transportation. In doing so fewer systems require development.

SPGD   (Space Power Generation and Distribution)

Power Beaming Applications

Satellites:

• Replacement of onboard power system

• Augmentation of onboard power supply

• Backup to onboard power supply

Orbital Transfer Vehicle
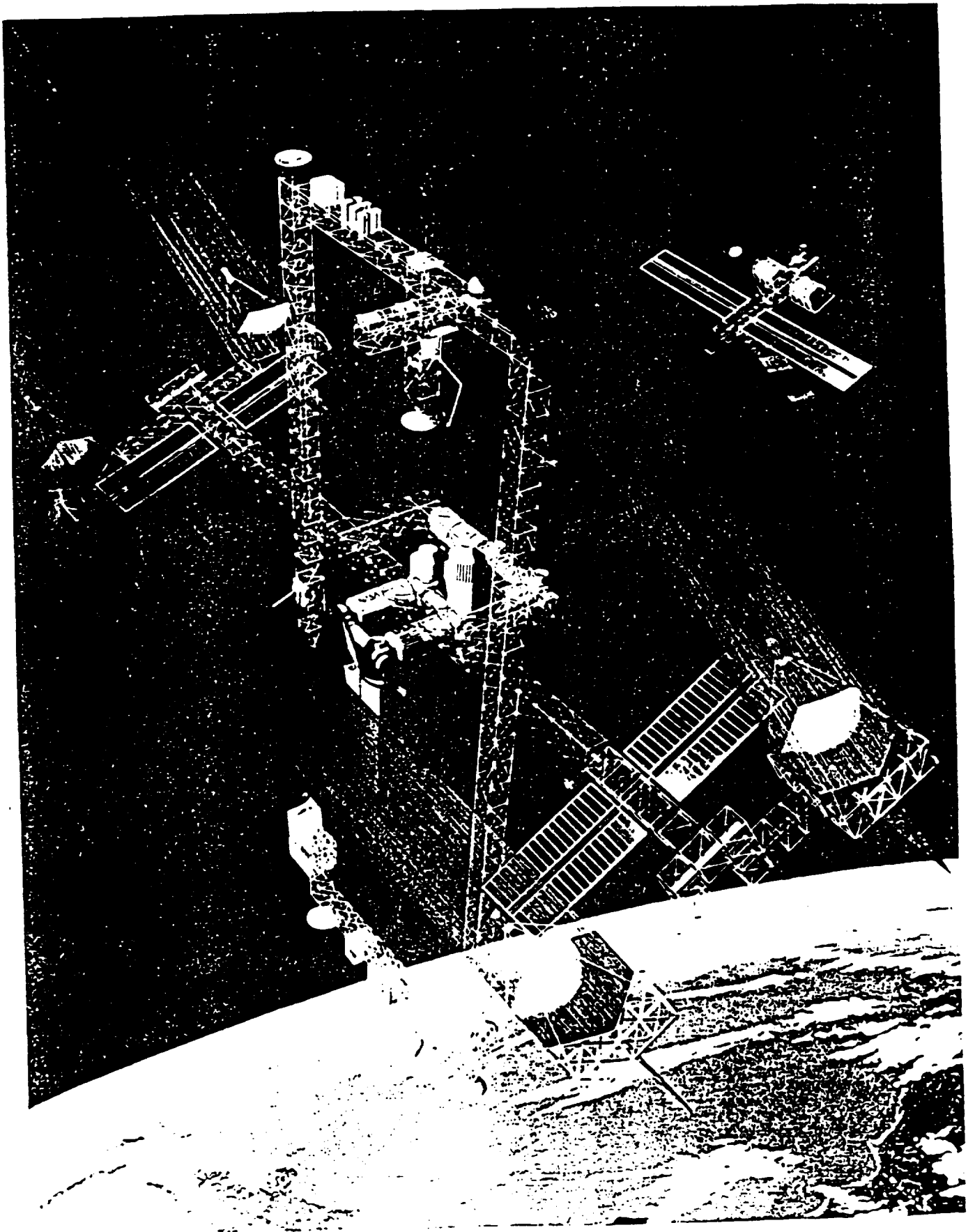
SPGD Application

- SPGD could provide power to any satellite In Earth orbit, particularly:
  - Space Station Freedom
  - Any satellite in low Earth orbit
  - Orbital transfer vehicles

- Provide power to foreign satellites in Earth orbit?

- Technology applicable to beam power usage for Lunar and Mars manned surface activities

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Near Earth Mission Options

- Utilities type power generation and distribution

- Beam-powered orbital transfer vehicle for LEO-GEO

- Power for space manufacturing and production

- Auxiliary power for space station and other manned systems

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L-11
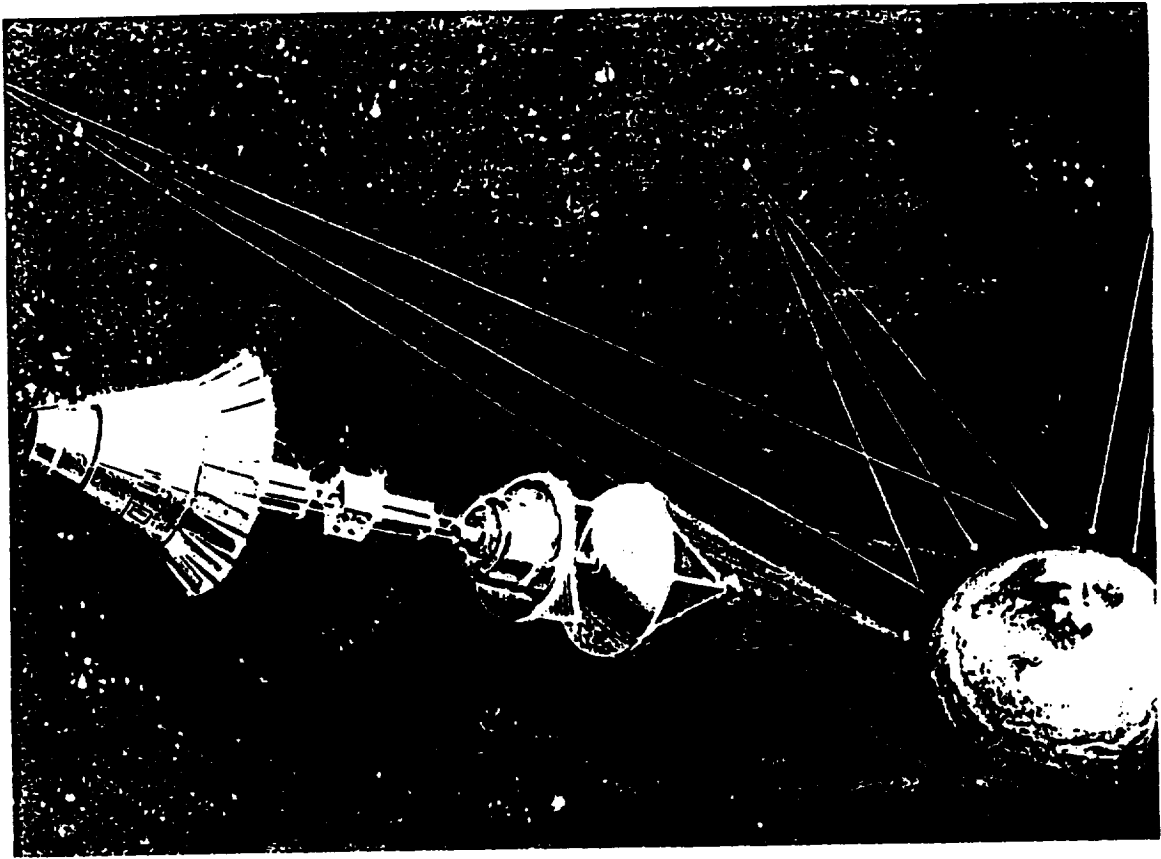
Electric Earth Orbital Transporter

- Fully modular reusable system

- Least mass on-orbit for satellite deployment

- Nuclear power source never on return trajectory

- Near term system building on existing technology base
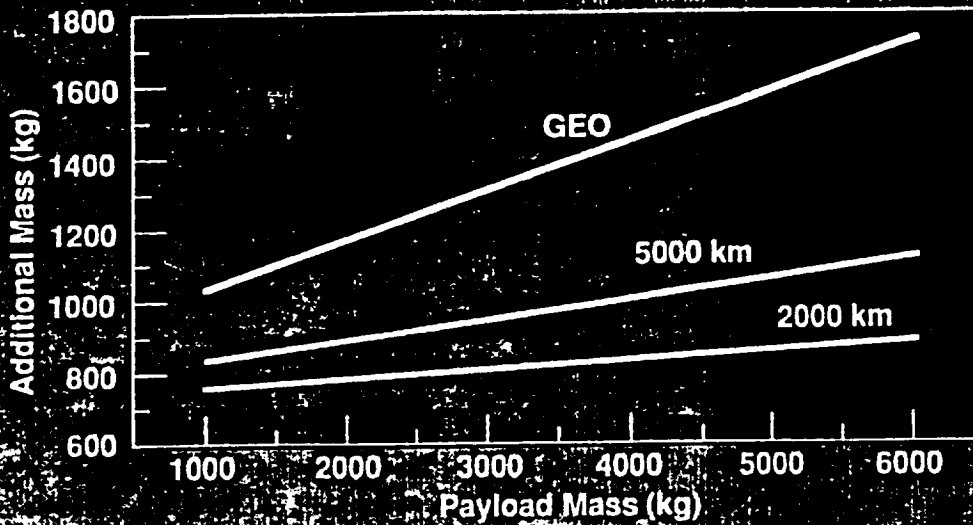
OTV Application

Beam-Powered OTV Capability

- 6000 kg payload capacity LEO to GEO

- 123 day round trip transfer time

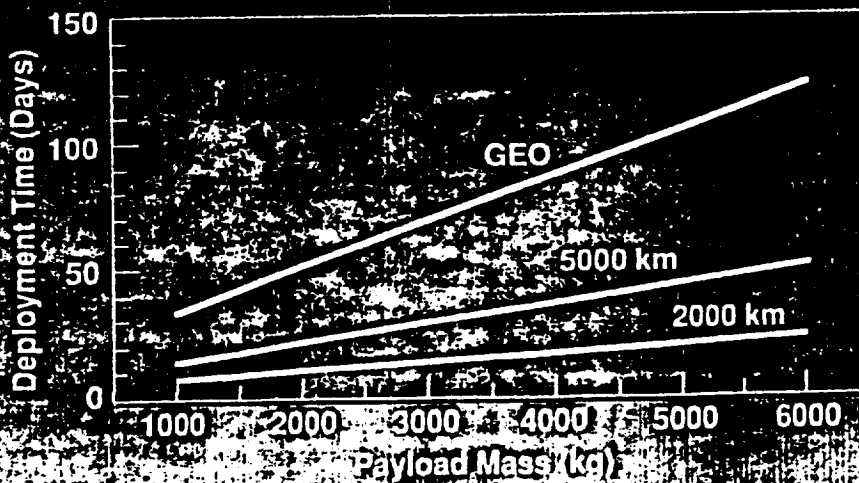- 40,000 kg payload capacity LEO to 5000 km with 100 day transfer time

Gross Launch Mass - Payload Mass

200 kW MPD Thruster Using Power Beaming

Deployment Time

200 kW MPD Thruster Using Power Beaming

Beyond Earth Orbit Missions

- Provides horizontal commonality of technology
  - Power Infrastructure transportable
  - Multifunctional hardware
  - Commonality of logistic support

- Cargo transport vehicle
  - Near earth power satellite power source
  - Near earth electric propulsion systems

- Planetary surface power
  - Addition of near earth power transmitter to cargo transport vehicle

Lunar/Mars Mission Applications

Technology enhances manned Lunar and Mars missions.
Power beaming provides a safe, reliable source of power
for extended surface activities.

- Use power supply for electric propulsion to transport cargo to Moon or Mars

- Beam power to surface after cargo discharge

- Assure surface systems operational and energy available prior to manned mission

- Power satellite available as back up for return to Earth in event of manned vehicle propulsion failure

OTV Applications for Lunar/Mars Missions

- Move cargo satellites from LEO to HEO

- Refuel reusable SEI satellites in HEO

- Transport cargo to/from reusable SEI satellites in HEO

- Remote maintenance on SEI satellites in HEO

- Move unmanned nuclear powered satellites to HEO for startup

- Salvage of failed satellites


Lunar Mission Options

- Continuous surface power available day and night

- No need to land major power source on the surface

- Power to multiple sites from a single power source

- Nuclear electric Lunar cargo vehicle doubles as the space based beam-power source
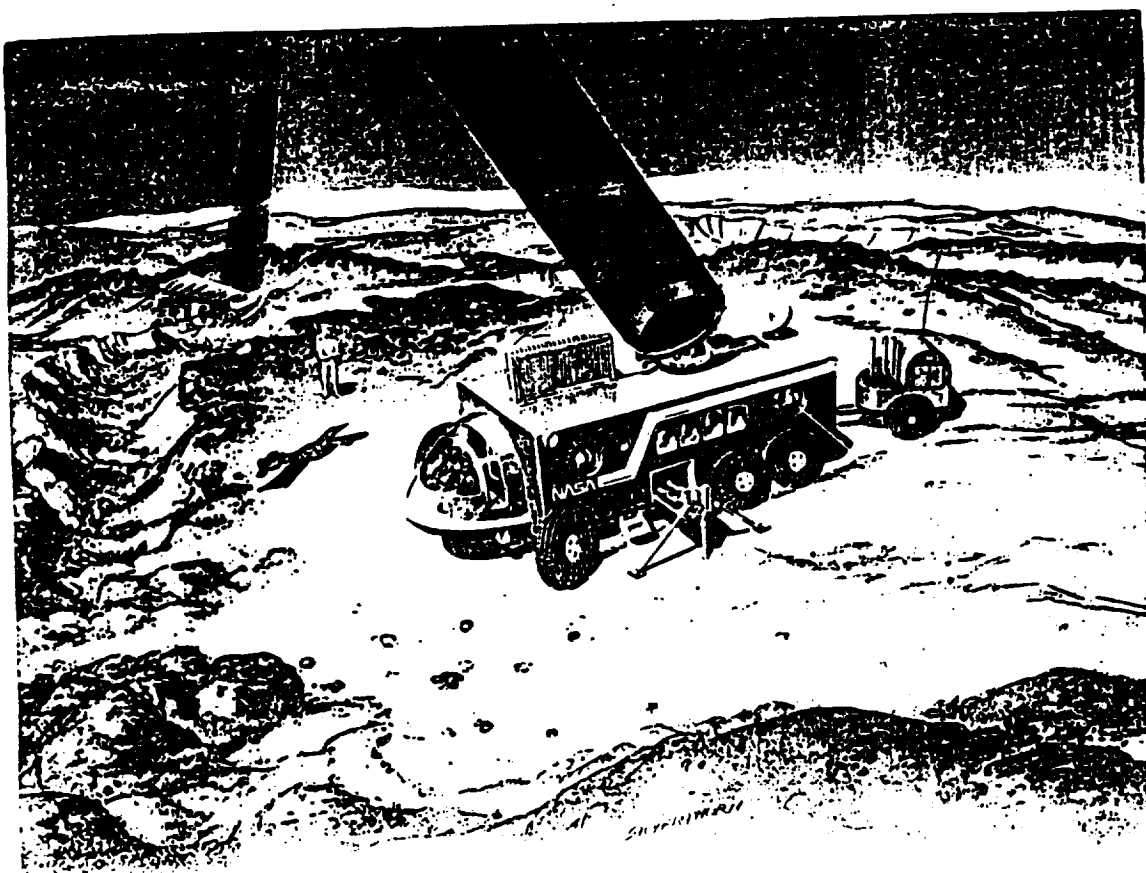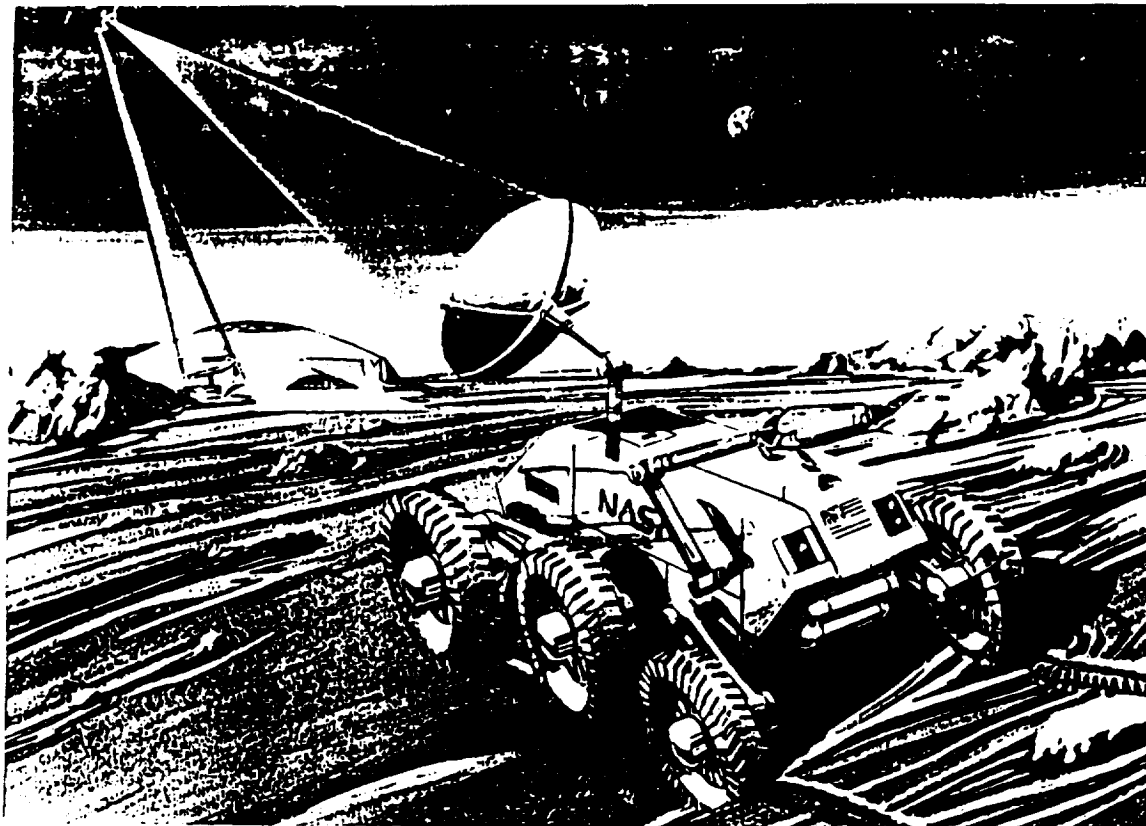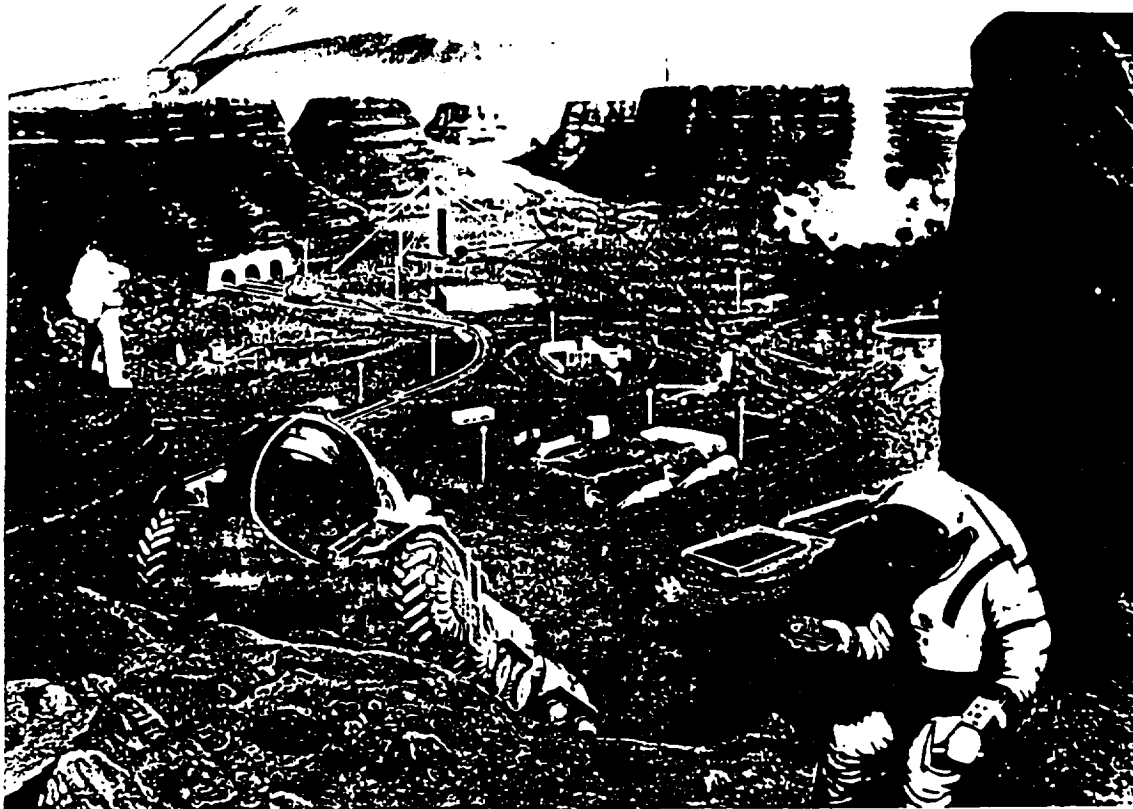
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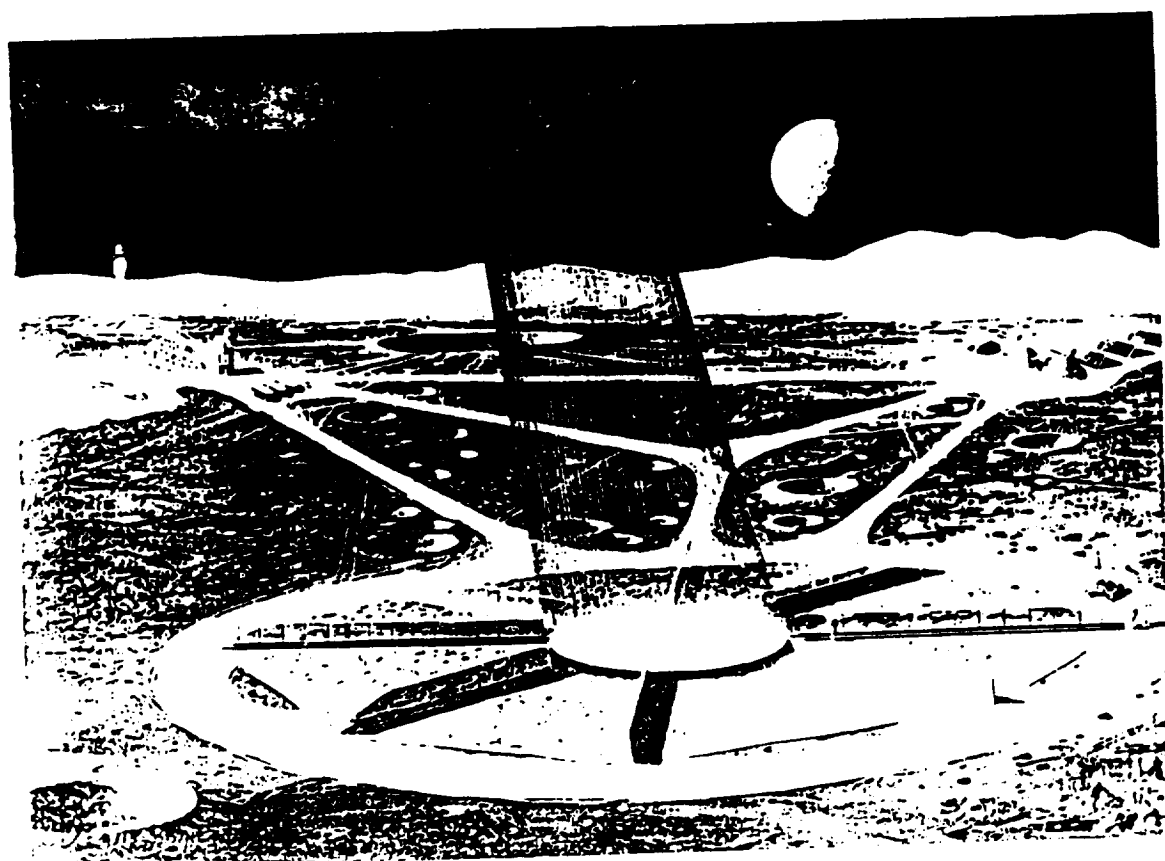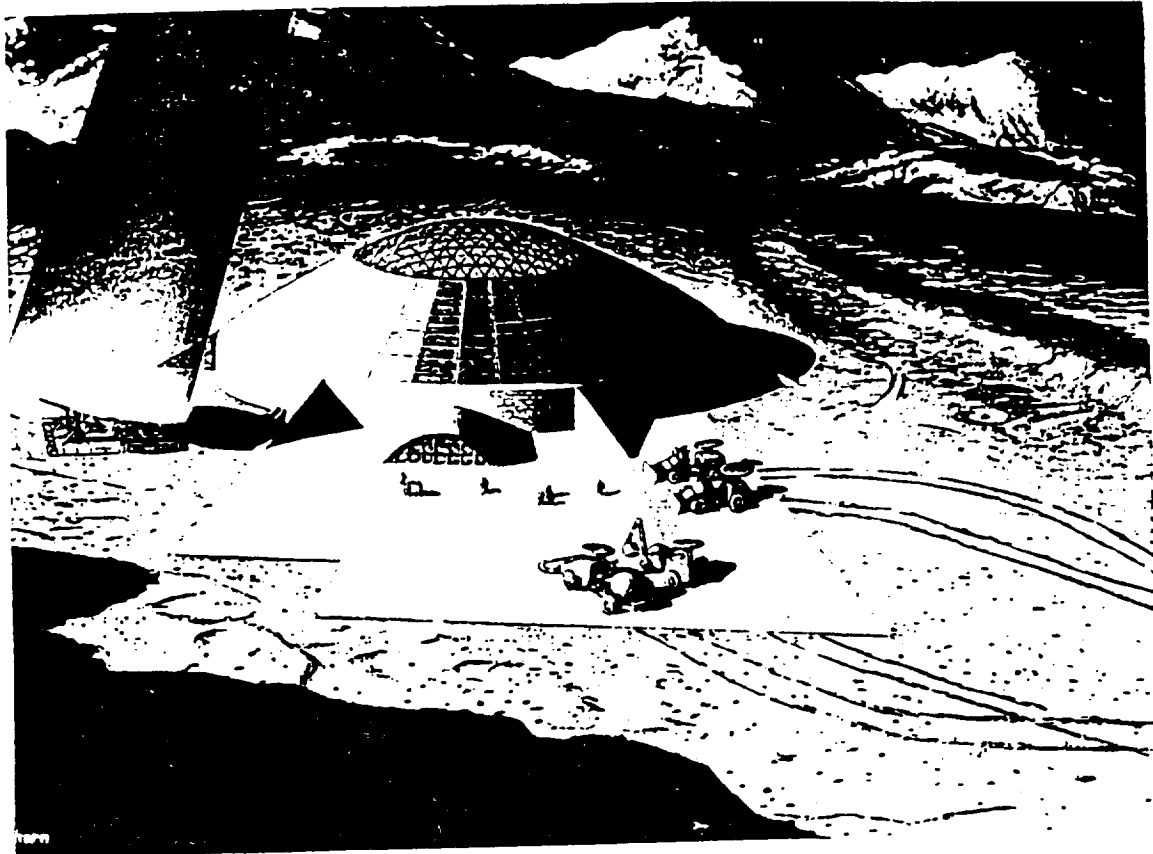
Mars Mission Options

- Nuclear electric Mars cargo vehicle doubles as space based beam power source

- Power for automated resource development

- Power available to support manned surface activities

  - Recharge surface transportation systems

  - prime power for a manned mars base both night and day

  - Power to support mining, manufacturing, fuel production, etc.

L-18
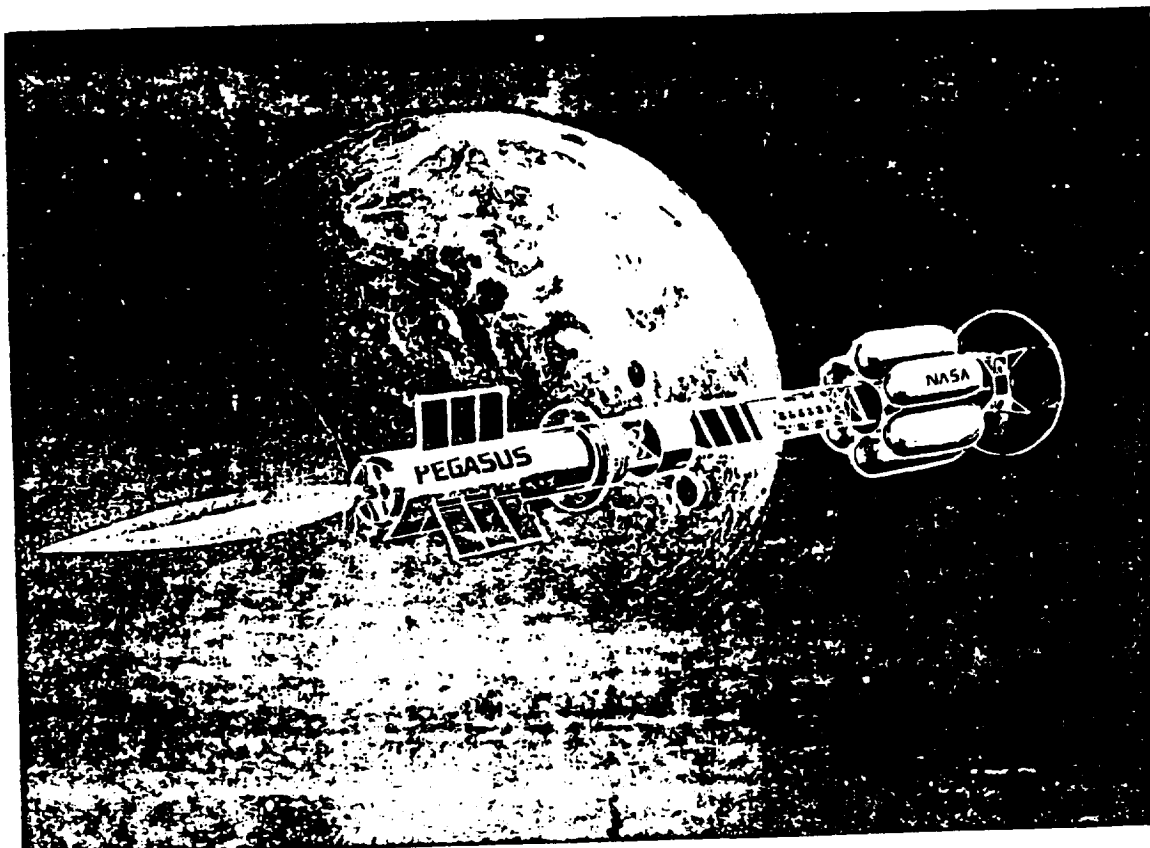
Mission Benefits and Enhancements

- Prime power source operational and tested

- No need to carry or land separate surface power system
  - Only receiver system landed and deployed
  - Receiver based on proven solar array technology

- No nuclear reactors on planet surface

- Megawatts of power available on surface

- Follow-on cargo transport vehicles
  - Provide redundant power sources
  - Meet growth in power requirements

SPGD (Space Power Generation and Distribution)

L-19

Mission Benefits and Enhancements (cont.)

- Emergency life support power requirements reduced
  - Receiver provides emergency power during daylight
  - Lunar crew return on extended outage
  - Mars night requires limited energy storage

- Surface transportation electric rechargeable
  - Fuel cell with H_2O storage and electrolysis
  - H_2/O_2 heat engine with H_2O storage and electrolysis
  - Regenerative fuel cell with electric recharge

- Surface transportation systems a source of emergency power for life support

---

Conclusions

- Provides unique new applications and significant mission enhancements

- Allows a greater number of users to benefit from space nuclear power

- Frees satellite designers and mission planners from concerns with onboard nuclear

- Separates power system development, deployment, and operation from mission specific requirements

- Provides the needed link between the user community and space nuclear power to allow user support of SNPS

PHOTON WAVELENGTH = 806 nm

PHOTON ENERGY = 1.54 eV

GaAs BAND GAP = 1.42 eV

1.54 eV   1.42 eV
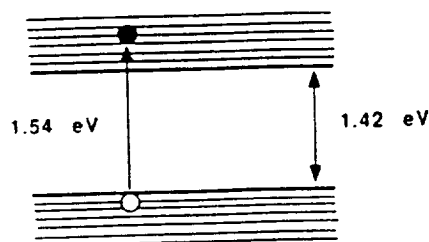
MAXIMUM CURRENT

J_{max} = q x [PHOTON FLUX]

$\quad = \dfrac{\text{INCIDENT POWER}}{\text{PHOTON ENERGY (eV)}} = 65 \dfrac{mA}{cm^2}$

FOR [INCIDENT POWER] = 100 $\dfrac{mW}{cm^2}$

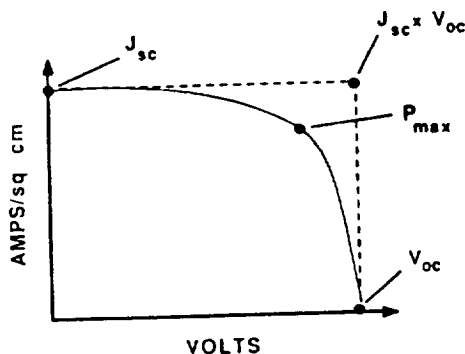CURRENT-VOLTAGE CHARACTERISTICS

$J_{sc} = Q_{EXT} \times J_{max}$

$J = J_{sc} - J_0 [\exp(V/kT) - 1]$

$P_{max} = J_{sc} \times V_{oc} \times FF$

$\text{EFFICIENCY} = \dfrac{100 \times \text{MAX POWER}}{\text{INCIDENT POWER}}$

J_{sc} $J_{sc} \times V_{oc}$

P_{max}

AMPS/sq cm

V_{oc}

VOLTS

CALCULATED MONOCHROMATIC GaAs CELL
EFFICIENCY FOR LASER AT 806 nm & 100 mW/cm^2

Q_{EXT} (%)	J_{SC} (mA/cm^2)	V_{OC} (VOLTS)	FILL FACTOR	EFFICIENCY (%)
100	64.9	1.07	.891	62.0
96.5 [1]	62.7	1.07	.891	59.8
95.0 [2]	61.7	1.07	.891	58.8

(1)   Assumed Reflection From Cell Surface Is 2% and Obscuration Due To Collector Grid Is 1.5 %.

(2)   Assumed Reflection From Cell Surface Is 2 % and Obscuration Due To Collector Grid Is 3 %.

(3) $J_0 = 6.0 \times 10^{-20} A/cm^2$. This Value Is An Experimentally Determined Value Based On Spire's Results For GaAs Cells.

(4)   Maximum Power And Efficiency Calculated Using J-V Characteristics And With PC-1D Computer Code .

EFFICIENCY VERSUS INTENSITY
FOR A GaAs CELL & 806 nm LIGHT

10 W Fiber-coupled laser

0.5 mm sampling, 2.0 mm step

```
0.000130
0.000124
0.000117
0.000111
0.000104
0.000098
0.000091
0.000085
0.000078
0.000072
0.000065
0.000059
0.000052
0.000046
0.000039
0.000033
0.000026
0.000020
0.000013
0.000007
0.000000
```

Experimental Setup

↑ - ANALOG

⋮ - GPIB

▌ - DIGITAL BUS

L-23

BANDGAP (eV)

WAVELENGTH (μm)

L-24
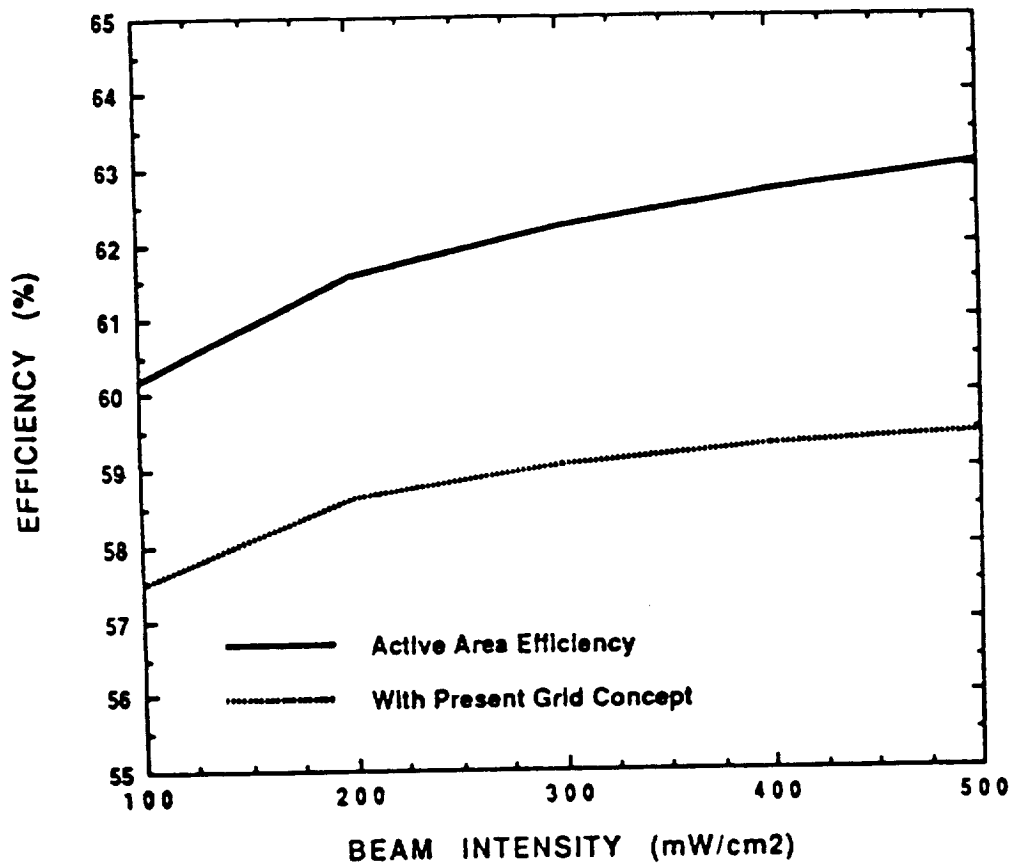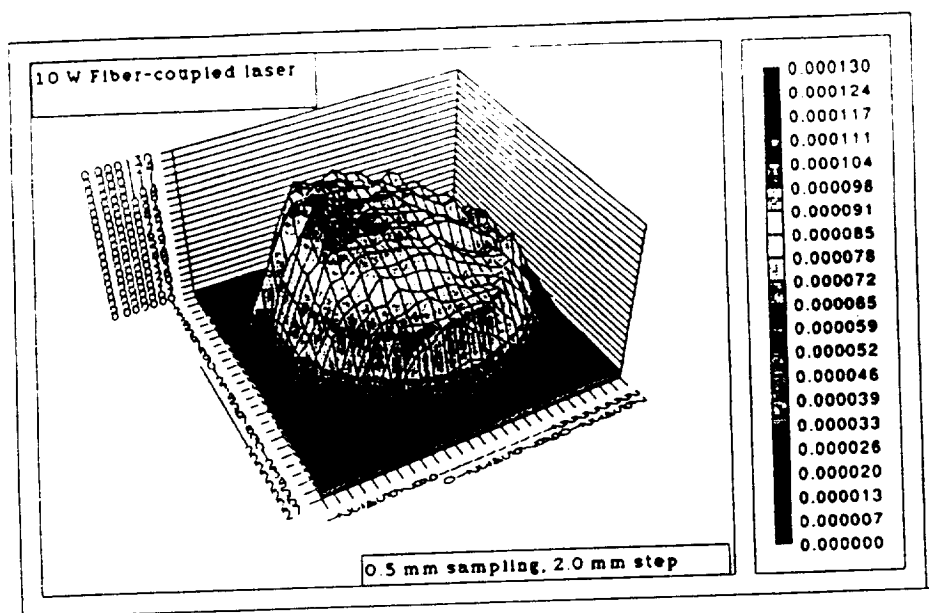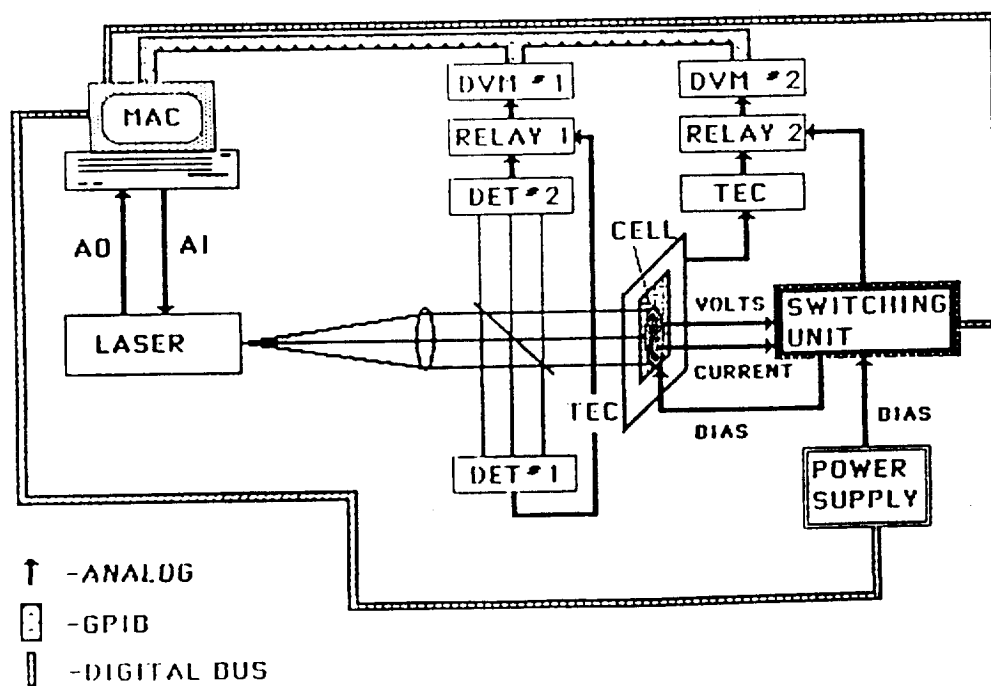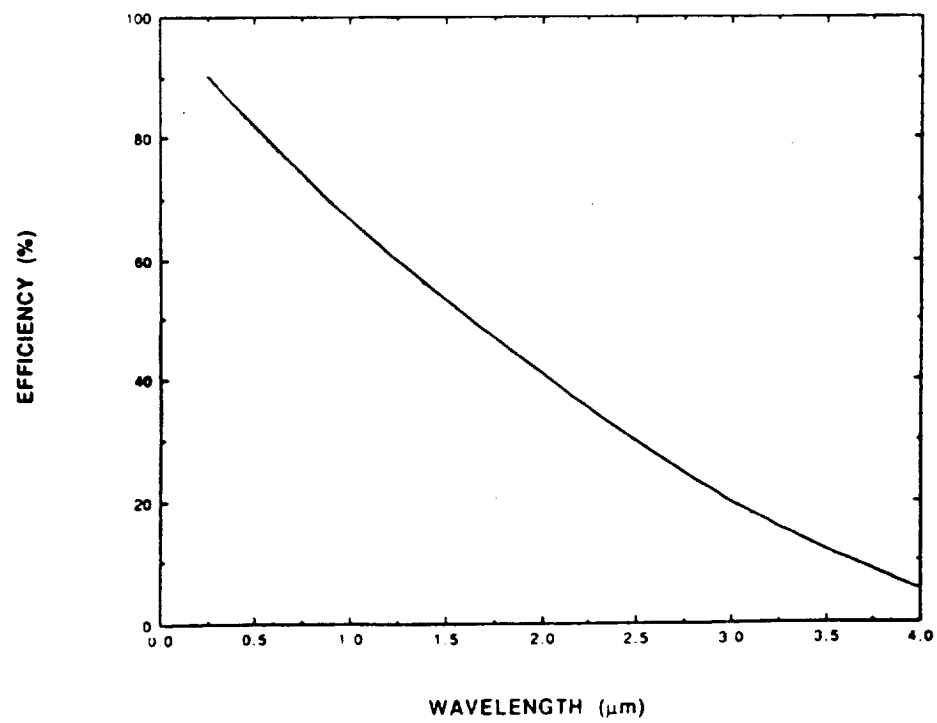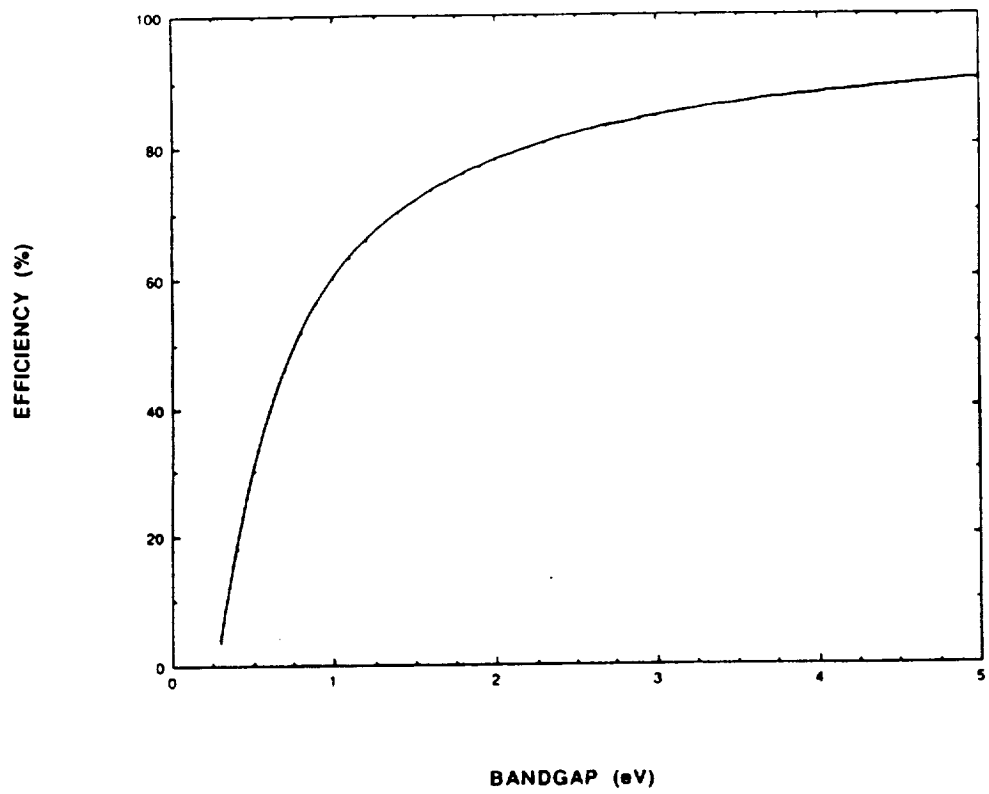
WSU TRI-CITIES PHOTOVOLTAICS RESEARCH LABORATORY

PERSONNEL

- Dr. Larry C. Olsen (Principal Investigator)

- Dr. F. William Addis (Cell Fab and Analyses)

- Mr. Glen Dunham (MOCVD Growth)

- 3 - 6 Graduate Students (Ph.D & M.S.)

PV EXPERIENCE

- Involved In Photovoltaic Research Since 1974.

- Programs Have Involved Studies of Silicon, Copper-Indium-Diselenide, and III-V Compounds.

- Fabricated GaAs Cells with AM0 Efficiency > 19%.

- Fabricated Monochromatic GaAs Cells with an Efficiency of 54% at 806 nm and 100 mW/cm².

WSU PV RESEARCH LABORATORY (CONT.)

FACILITIES

- PV Research Facilities Include Four Laboratories Covering 2000 ft².

SOLAR CELL FABRICATION

- SPIRE 500 XT MOCVD System for Growth of GaAs, AlGaAs, InGaAs, InP, and ZnSe Films and Devices.
- 5 Vacuum Deposition Systems and PECVD for Metal and Anti-Reflection Coatings.
- Vertical Laminar Flow Wet Bench for Processing.
- Tube Furnaces with Gas Delivery System For
- Photolithography Laboratory

DEVICE CHARACTERIZATION

- Solar Simulator with Data Acquisition.
- Photoresponse and T-I-V Measurement Stations.
- BIO-RAD Polaron Electrochemical C-V Profile Plotter for Dopant Concentration Profiling.
- SEM and Other Capabilities for Characterizing Films and Device Structures.

SOLAR CELL MODELING AND DATA ANALYSES

- Utilize PC-1D Computer Code for Cell Modeling.
- Numerous Codes for Analyzing Optical Properties of Multilayered Structures.

PHOTOCURRENT (A) / VOLTAGE (V)

CELL IDENTIFIER: NASA.1.laser.1
DATE: 9/24/90
TIME: 9:10 AM

Pvolt_max: 0.43765
Pcurr_max: 0.13582
Power_max: 0.05949
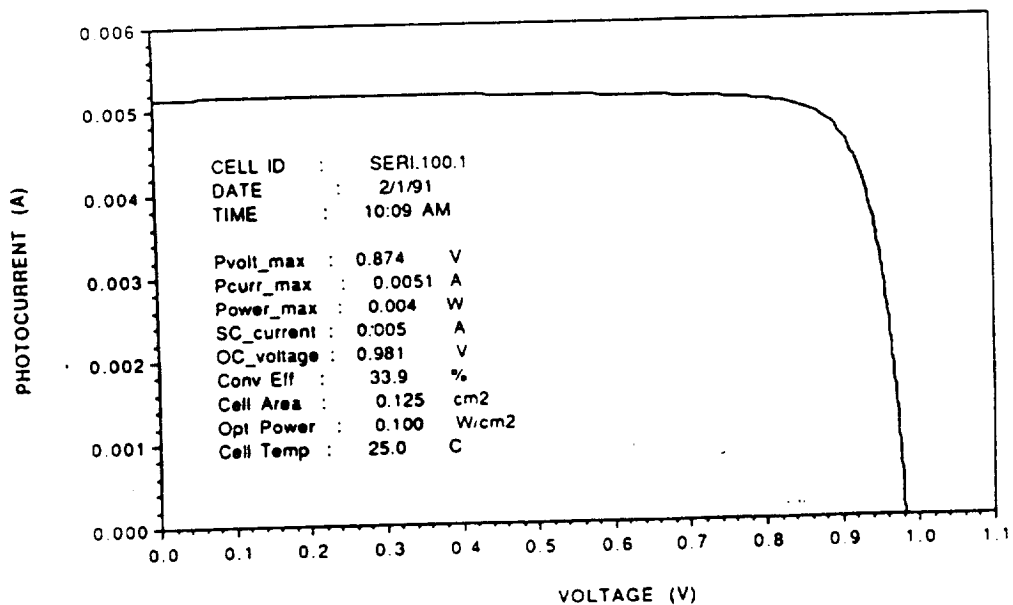Fill_factor: 0.67890
SC_current: 0.15029
OC_voltage: 0.58302
Conver. Eff.: 0.18432
Cell Area: 3.62
Res. Val.: 1.53000
Cell Temp.: 25.4

Battelle NW Laboratory
Power Beaming Laboratory

MAX POWER PT.

Data from "SERI.100.1"

CELL ID   :   SERI.100.1
DATE   :   2/1/91
TIME   :   10:09 AM

Pvolt_max   :   0.874   V
Pcurr_max   :   0.0051   A
Power_max   :   0.004   W
SC_current   :   0:005   A
OC_voltage   :   0.981   V
Conv Eff   :   33.9   %
Cell Area   :   0.125   cm2
Opt Power   :   0.100   W/cm2
Cell Temp   :   25.0   C

L-27

Top plot:

PHOTOCURRENT (A)

0.1300
0.1200
0.1100
0.1000
0.0900
0.0800
0.0700
0.0600
0.0500
0.0400
0.0300
0.0200
0.0100
0E0

MAX POWER

CELL ID   : ASEC.19.100
DATE   : 1/22/91
TIME   : 11:33 AM

Pvolt_max : 0.89516 V
Pcurr_max : 0.11347 A
Power_max : 0.10156 W
Fill_fact : 81.64   %
SC_current : 0.12050 A
OC_voltage : 1.03254 V
Conv Eff   : 50.79   %
Cell Area : 2.00   cm2
Opt Power : 0.10000 W/cm2
Cell Temp : 25.0   C

Pacific Northwest Laboratory
Power Beaming Laboratory

0E0 0.1000 0.2000 0.3000 0.4000 0.5000 0.6000 0.7000 0.8000 0.9000 1.0000 1.1000

VOLTAGE (V)

Bottom plot:

PHOTOCURRENT (A)

0.0500
0.0400
0.0300
0.0200
0.0100
0E0

MAX POWER

CELL ID   : 808sAs31D3
DATE   : 1/24/91
TIME   : 2:45 PM

Pvolt_max : 0.902 V
Pcurr_max : 0.048 A
Power_max : 0.043 W
Fill_fact : 85.4   %
SC_current : 0.049 A
OC_voltage : 1.080 V
Conv Eff   : 54.1   %
Cell Area : 0.79   cm2
Opt Power : 0.100 W/cm2
Cell Temp : 25.0   C

Pacific Northwest Laboratory
Power Beaming Laboratory

0E0 0.1000 0.2000 0.3000 0.4000 0.5000 0.6000 0.7000 0.8000 0.9000 1.0000 1.1000

Voltage (5)

L-28

Summary

Power beaming has the potential to:

- Substantially reduce SEI costs
- Provide an early, affordable, major enhancement in U.S. space leadership
- Substantially enhance mission safety
- Substantially enhance mission flexibility
- Provide early, major technology spin-offs
- Provide an early, continuing return on investment
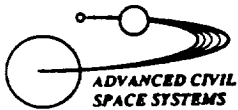- Provide substantially enhanced commercialization opportunities

R9010017. 13

L-29

Power Beaming

Lunar Surface Power Requirements and the
SPS Laser Analysis

Brent Sherwood
Brad Cothran

Cleveland, Ohio
February 5, 1991

BOEING

Summary of Boeing Work Related to
Power Beaming

ADVANCED CIVIL SPACE SYSTEMS — *BOEING*

- Past involvement with the SPS program provided experience and insight into power beaming architectures and system integration (1980).

- Other NASA funded studies analyzed surface systems and their associated power requirements (1988).

- Key participation in NASA Lunar Energy Enterprise Study (1989).

- Current 4 year contract to demonstrate space based laser technology (originally the ground based FEL).

- Current NASA/MSFC study contract includes power beaming task to analyze electric orbit transfer systems.

ADVANCED CIVIL
SPACE SYSTEMS

BOEING

- Major concern of lasers during the SPS analysis was the conversion efficiency of electric to laser was low.

- For ground based power beaming sources, electric to laser efficiency is not a big issue.

- Lasers offered two potential benefits:
    - Transfer smaller blocks of power; broaden market
    - Less environmental concerns

- Lasers were less efficient than microwaves. Proposed substantially improving at least one end of the link.

- Laser technology has advanced since the SPS analysis. Much work is classified.

STC AEM/brc/4Feb91/disk 10

ADVANCED CIVIL
SPACE SYSTEMS

Study Objectives

BOEING

SPS Laser Analysis

1. Evaluate and select laser technologies having promise for the SPS power transmission application.

2. Develop candidate SPS system concepts using laser power transmission.

3. Select a "reference" system and provide a comprehensive evaluation.

4. Determine critical issues associated with laser SPS systems and develop a five year ground-based exploratory development plan for key elements of the laser SPS system.
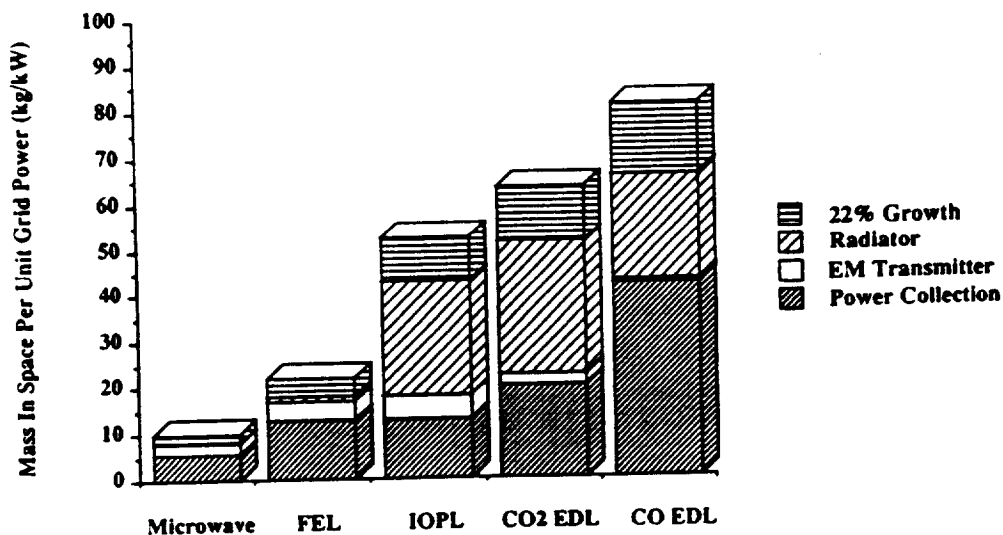
STC AEM/brc/4Feb91/disk 10

SPS Laser Analysis

- The most promising laser for the SPS application is the FEL.

- The FEL is inherently lighter, scales nicely to commercial utility power levels, and exhibits a distinct advantage in having a tunable wavelength to enhance atmospheric transmission.

- The IOPL was recognized as the second choice.

- Almost all aspects of laser SPS's require technology development.

- Although much analysis was based on future technology, no "can't possibly do's" were identified.

STC AEM/brc/4Feb91/disk10

ADVANCED CIVIL
SPACE SYSTEMS

Laser SPS Option Masses

BOEING

STC AEM/brc/4Feb91/disk10

SPS Laser Analysis

In order for establish technical feasibility of the laser alternative to SPS, recommendations in the following areas for a ground based exploratory development program were made:

- Electron Discharge Lasers

- Indirect Optically Pumped Lasers

- Free Electron Laser

- Optical beam control for all lasers

- Laser power receivers

STCAEM/bc/4Feb91/disk10

Robotic Lunar Surface Operations

Engineering Analysis for the Design, Emplacement, Checkout

and Performance of Robotic Lunar Surface Systems

Study performed for

NASA Ames Research Center

under Contract NAS 2 - 12108

Boeing Aerospace & Electronics
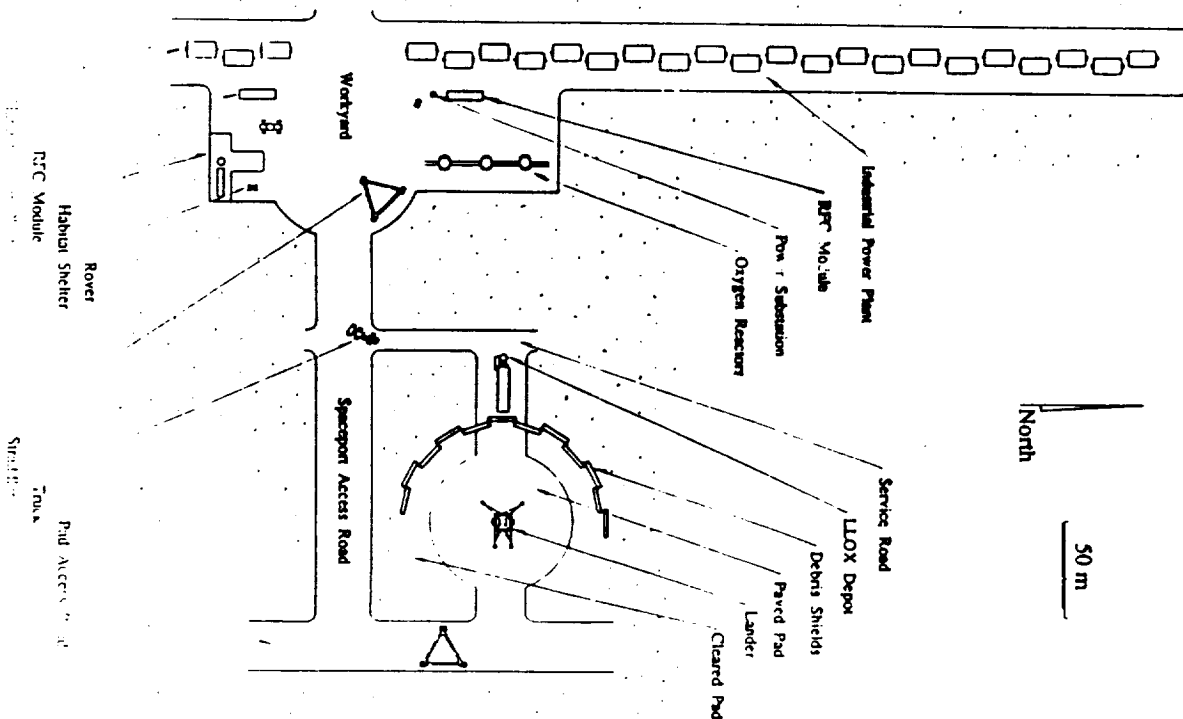
## Huntsville AL

2 January 1990

D 615 - 11 901
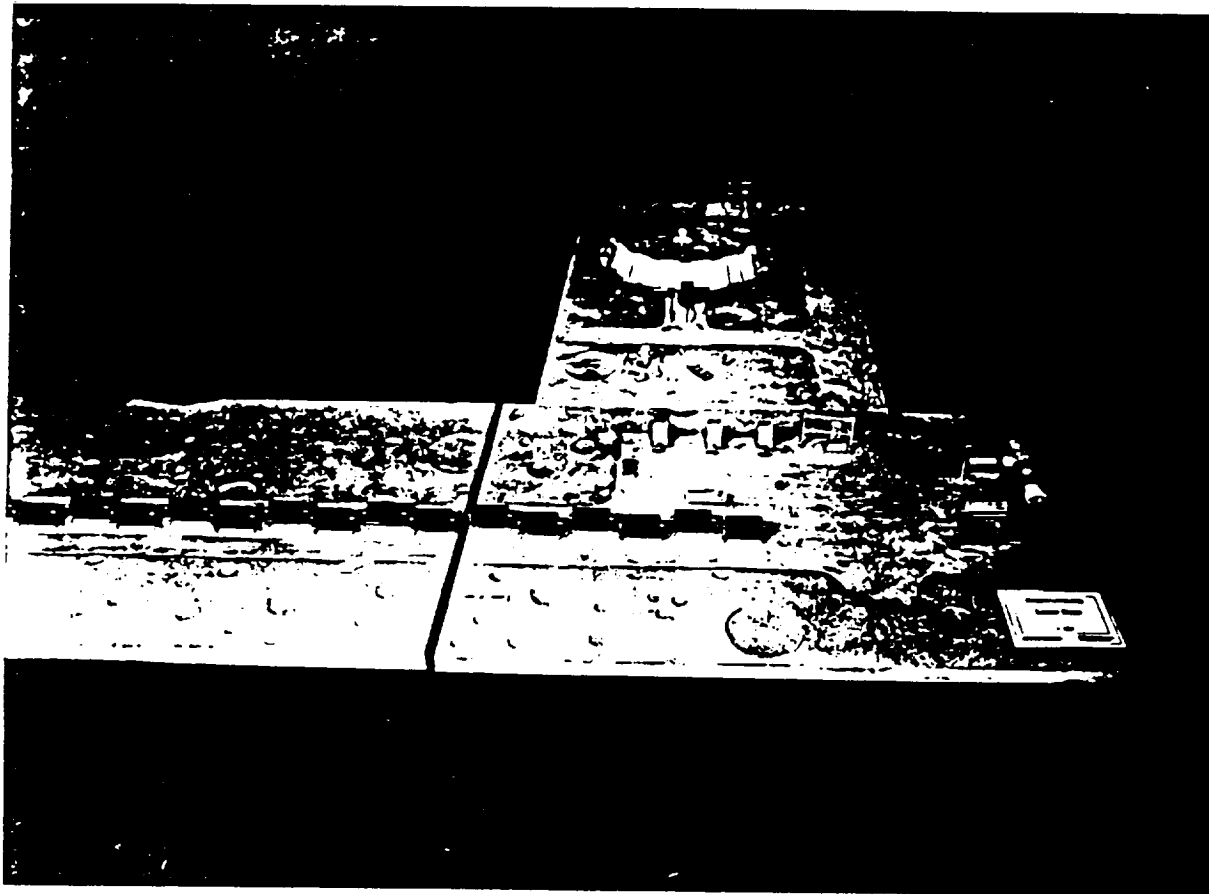
Lunar Base Site Plan

BOEING

Workyard

Rover
RFC Module
Habitat Shelter

Spaceport Access Road

Industrial Power Plant
RFC Module
Power Substation
Oxygen Reactor

Service Road
LLOX Depot
Debris Shields
Paved Pad
Lander
Cleared Pad

North

50 m

Assume: 13 28d diurnal cycles per year available
12 cycles working time, 1 cycle down
100 t LLOX total production (875 m³) per year
3 oxygen reactors, each produces 33 t/yr
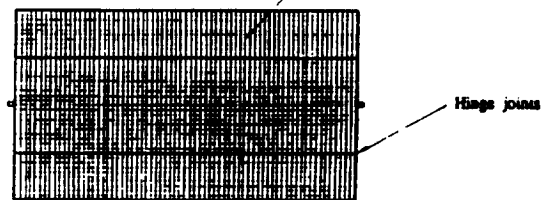1.7 t/m³ piled bulk density
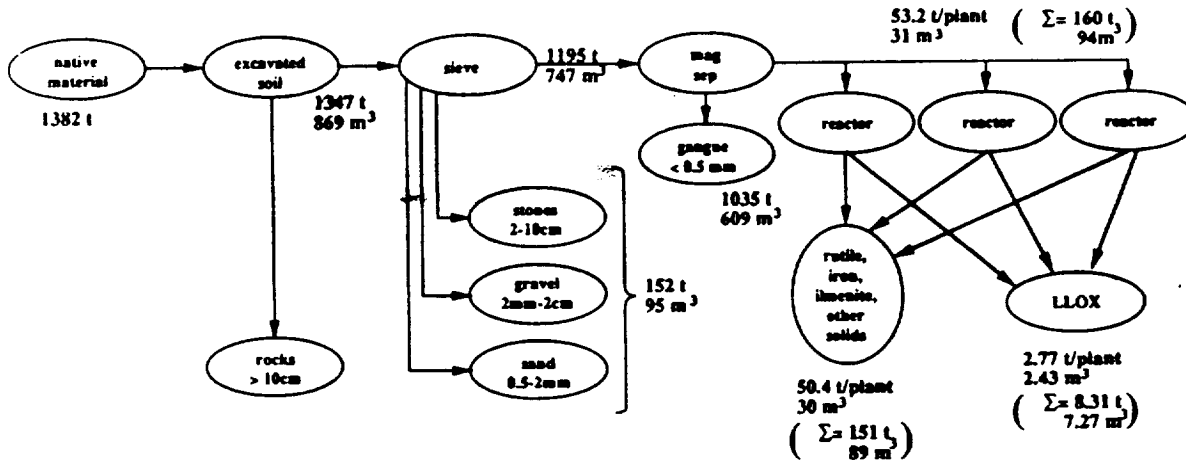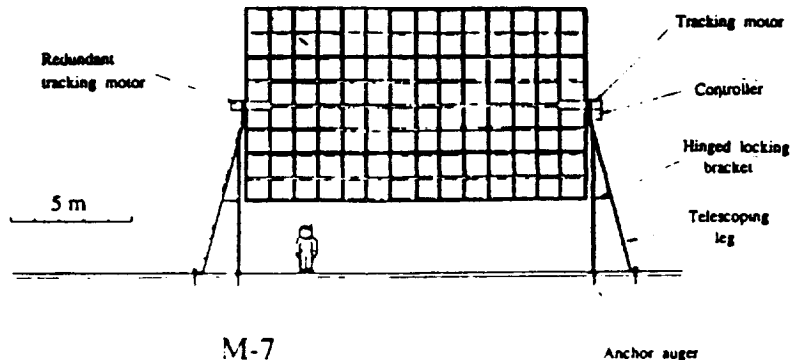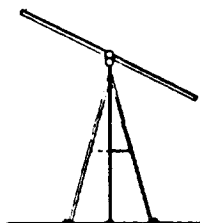

M2/37/02/GJ

Freestanding 20kWe Solar Array

BOEING

GaAs - on - Ge rigid cells
20 kWe total EOL @ 150°C

-- 20 kWe total EOL output @ 150°C
-- Solar tracking, axis oriented north - south
-- Transported folded, with active surface protected
-- Deployed by straddler manipulators while hanging
-- No assembly required, only connections to bus
-- 1.25 mt total mass

Hinge joints

Fin - composite
waffle plate
backup structure

Redundant
tracking motor

Tracking motor

Controller

Hinged locking
bracket

Telescoping
leg

5 m

Anchor auger

STS Payload Bay - Size Pallet

Sunshade

Deployable Radiator

1500 psi GO2 Tank

1500 psi GH2 Tank (2)

Pumps and Valves

Electrolyzers

Instrumentation and Control

Water Holding Tank

Fuel Cells

H2 tanks	7
O2 tanks	3.5
Reactants	4.2
Water tanks	0.5
Pump packs	0.3
Electrolyzers	0.3
Fuel Cells	0.3
Plumbing	0.3
Control Electronics	0.1
Power Processing	0.3
Cabling	0.1
TCS	1
Pallet	4
Mass growth	3.5
	25.4 mt

40 kWe input to electrolyzers

20 kWe output from fuel cells
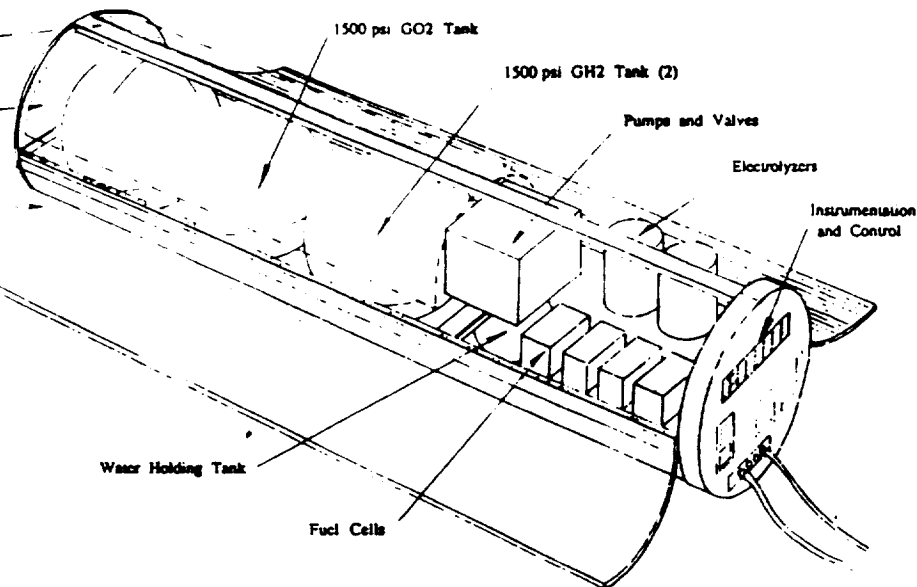
Lunar Ilmenite Oxygen Reactor

ADVANCED CIVIL SPACE SYSTEMS

BOEING

TABI insulation (7 cm)

C / C Pressure vessel (6 cm)

Alumina liner (2 mm)

Feed / empty / clean hatch

Rack and pinion drive

Static solids level

Gimbal stand

Hopper cart rails

Naturally compacted regolith

Circulation pump

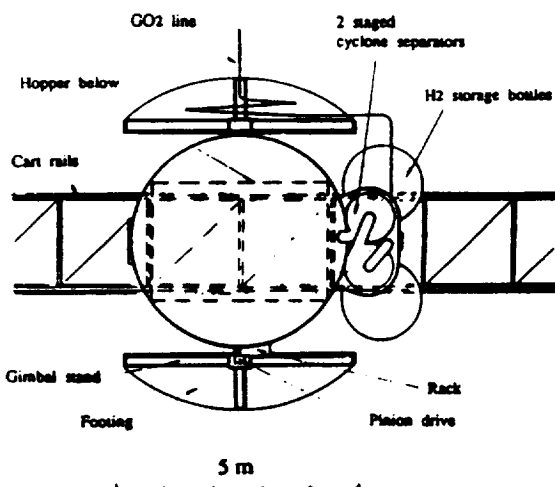2 staged cyclone separators

H2 / H2O line

GO2 line

Zirconia electrolyzer

Evacuation compressor

H2 bottle

Distribution plenum

27 mt capacity hopper

GO2 line

2 staged cyclone separators

Hopper below

H2 storage bottles

Cart rails

Gimbal stand

Rack

Footing

Pinion drive

5 m

-- Fluid - bed batch reactor, process at 10 atm, 900° C
-- 53.2 mt, 55 % enriched ilmenite regolith charge (< 2 mm)
-- 133 kWe heat - up power
-- 150 hr heat - up, 150 hr process run
-- Gas composition nominally 90 % hydrogen, 10 % steam
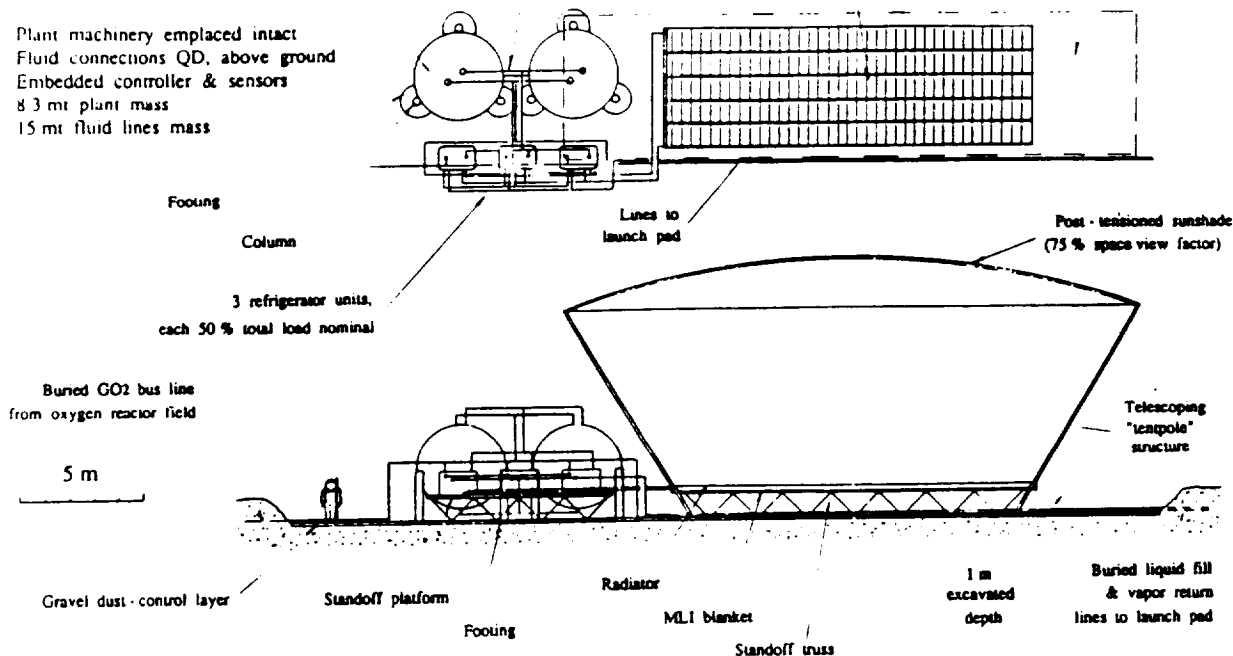-- 30 mt total mass, landed intact

M-8

2 Al LLOX tanks
(each holds full lander capacity)
MLI, polished Al debris /sun shield

Liquid fill &
vapor return lines

5 ganged 1 x 15 m
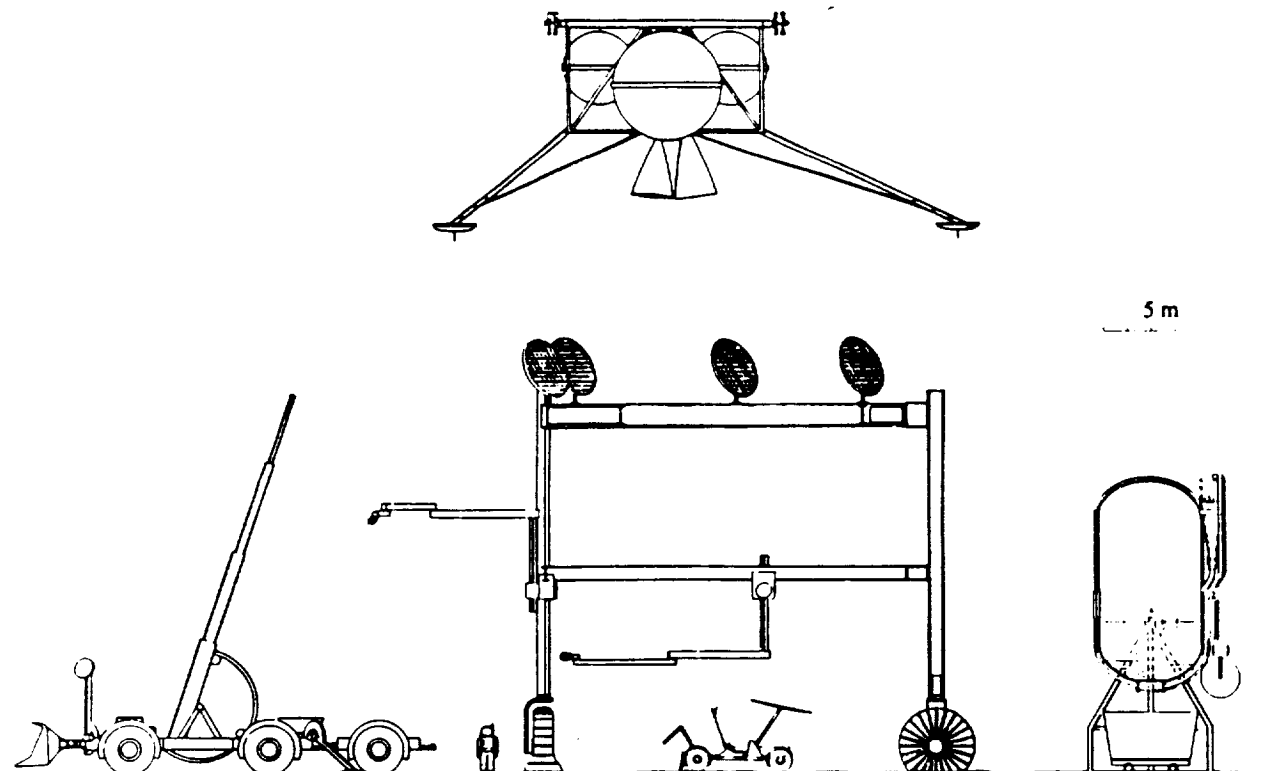radiator modules

Sunshade
overhang

- Plant machinery emplaced intact
- Fluid connections QD, above ground
- Embedded controller & sensors
- 8.3 mt plant mass
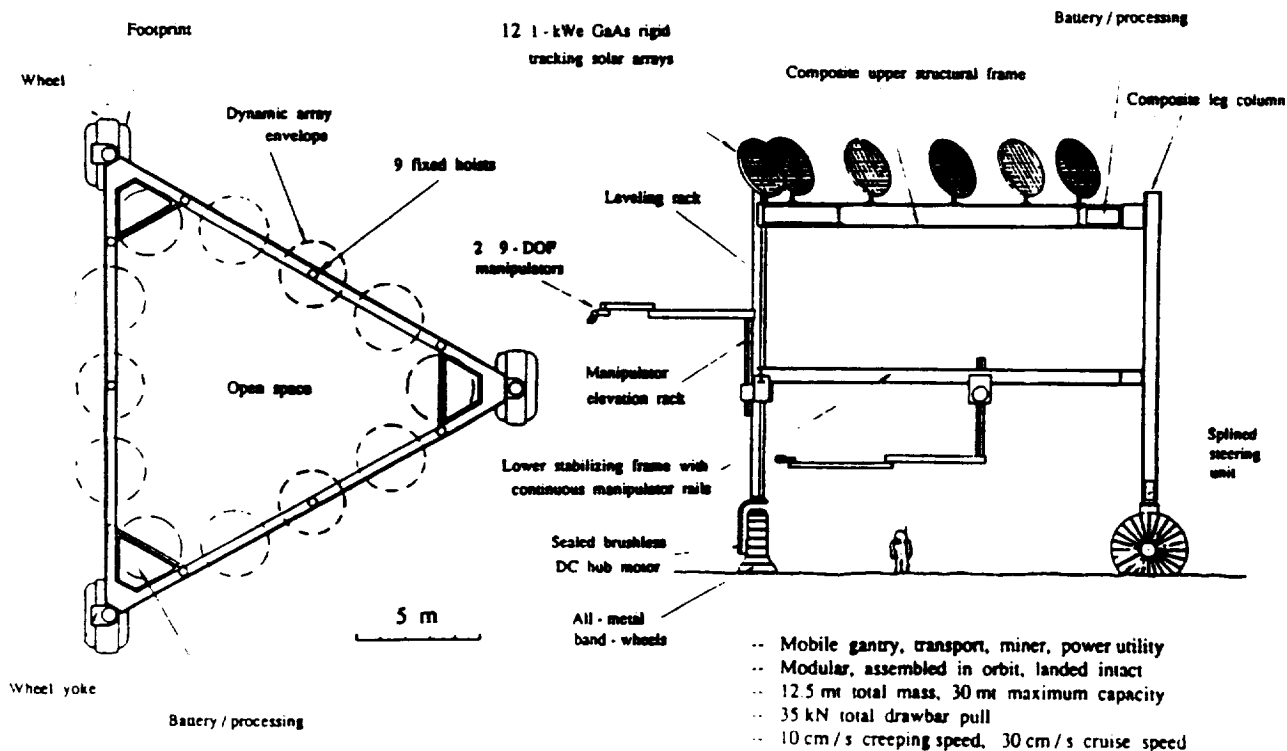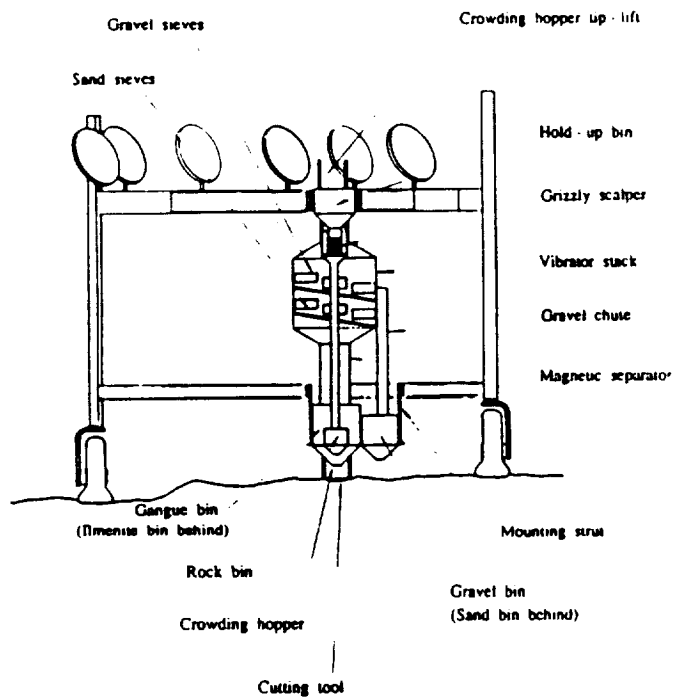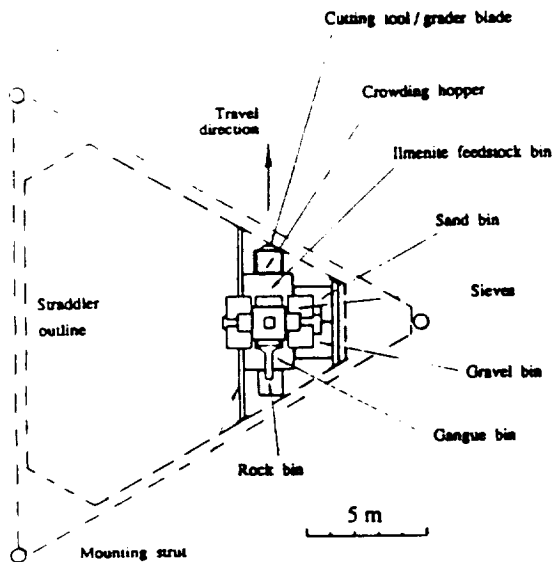- 15 mt fluid lines mass

Footing

Column

3 refrigerator units,
each 50 % total load nominal

Lines to
launch pad

Post - tensioned sunshade
(75 % space view factor)

Buried GO2 bus line
from oxygen reactor field

Telescoping
"tentpole"
structure

5 m

Gravel dust - control layer

Standoff platform

Footing

Radiator

MLI blanket

Standoff truss

1 m
excavated
depth

Buried liquid fill
& vapor return
lines to launch pad

| Functions \ Tasks	Site survey	First cargo down	Cargo unloading	Landing pad prep	Road building	Transfer line deploy	PV deployment	Habitat emplacement	Regolith shelter setup	Radiator / sunshade setup	Comm system inst'l	RFC emplacement	Oxygen reactor setup	LLOX depot setup	Ilmenite mining	Ore transport	Gangue deposition	Ox reactor loading	Ox reactor dump	Ox rctr clng & servc'g	Moving disabled lander	Servicing lander	Servicing PV unit	Servicing RFC	Servicing utilities	Servicing robots
Self - Unload	●	●																								
Light mobility, materials & equipment transport	●		●		●	●		●	●	●				●							●		●	●	●	●
Heavy mobility, materials & equipment transport		●	●	●	●		●	●				●	●	●	●	●	●	●			●					
Light low - lift / positioning			●			●	●	●	●				●											●	●	●
Light high - lift / positioning			●				●		●	●	●							●			●		●	●		●
Heavy low - lift / positioning		●	●	●				●	●			●	●	●	●		●		●					●		●
Heavy high - lift / positioning		●	●						●				●			●			●		●		●			●
Light materials placement	●		●			●	●		●	●	●			●							●		●	●	●	●
Heavy materials placement		●	●	●			●	●			●	●					●		●	●		●	●	●	●	●
Manipulation / tool use	●	●	●			●	●	●	●	●	●	●	●	●				●			●	●	●	●	●	●
Excavation / grading			●	●	●	●	●						●	●	●		●									

5 m

ADVANCED CIVIL SPACE SYSTEMS

Straddler

BOEING

Footprint

12 1-kWe GaAs rigid tracking solar arrays

Battery / processing

Wheel

Composite upper structural frame

Composite leg column

Dynamic array envelope

9 fixed hoists

Leveling rack

2 9-DOF manipulators

Open space

Manipulator elevation rack

Lower stabilizing frame with continuous manipulator rails

Splined steering unit

Sealed brushless DC hub motor

5 m

All - metal band - wheels

Wheel yoke

Battery / processing

-- Mobile gantry, transport, miner, power utility
-- Modular, assembled in orbit, landed intact
-- 12.5 mt total mass, 30 mt maximum capacity
-- 35 kN total drawbar pull
-- 10 cm / s creeping speed, 30 cm / s cruise speed

M-10

ADVANCED CIVIL SPACE SYSTEMS

BOEING

Cutting tool / grader blade

Crowding hopper

Ilmenite feedstock bin

Travel direction

Sand bin

Sieves

Straddler outline

Gravel bin

Gangue bin

Rock bin

5 m

Mounting strut

Gravel sieves

Sand sieves

Crowding hopper up · lift

Hold · up bin

Grizzly scalper

Vibrator stack

Gravel chute

Magnetic separator

Gangue bin
(Ilmenite bin behind)

Rock bin

Crowding hopper

Gravel bin
(Sand bin behind)
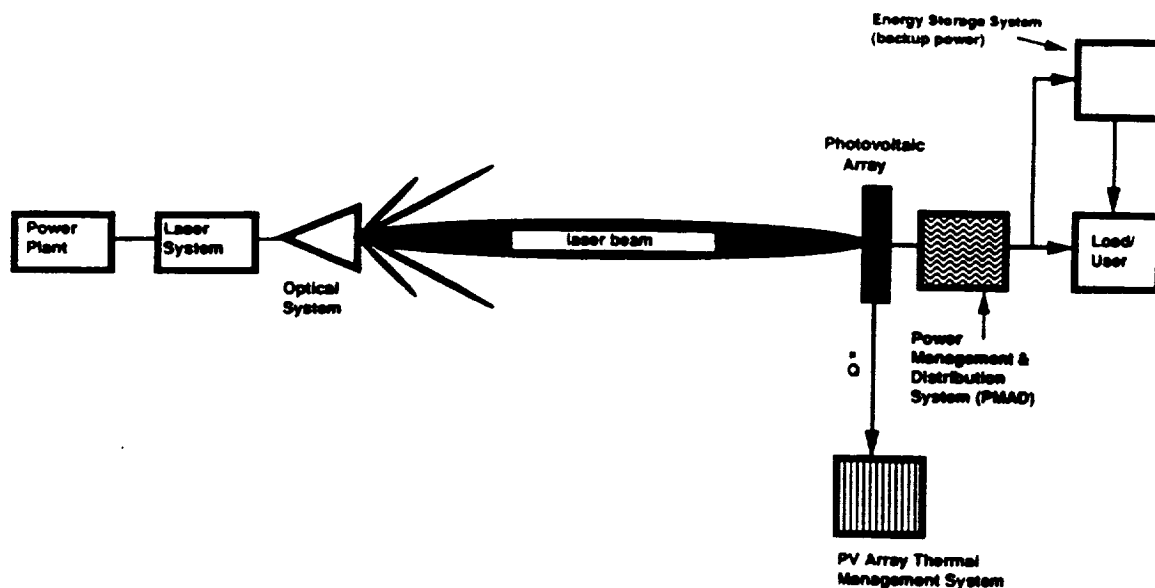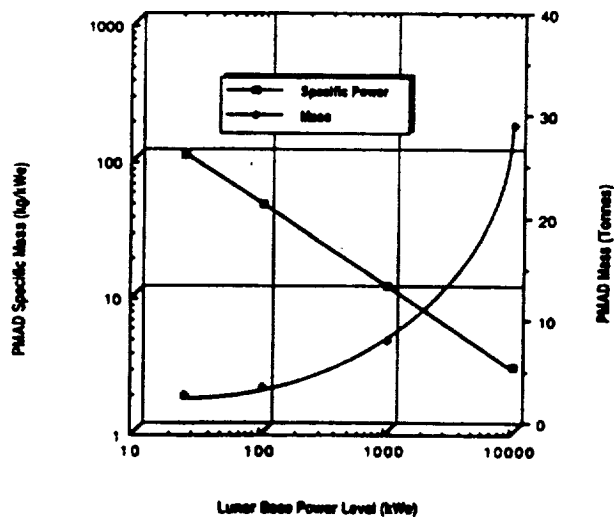
Mounting strut

Cutting tool

-- Grades, levels, exposes flat undisturbed subgrade
-- Mines unprepared substrate, beneficiates during transport
-- Rejects rocks > 10 cm, retains all else
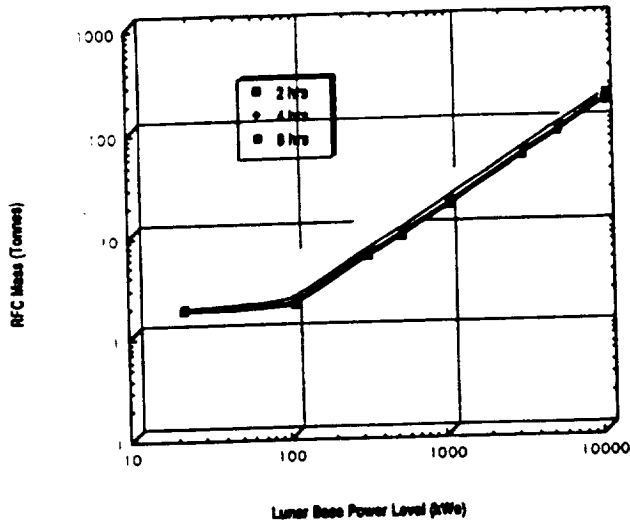-- 10 mt total mass
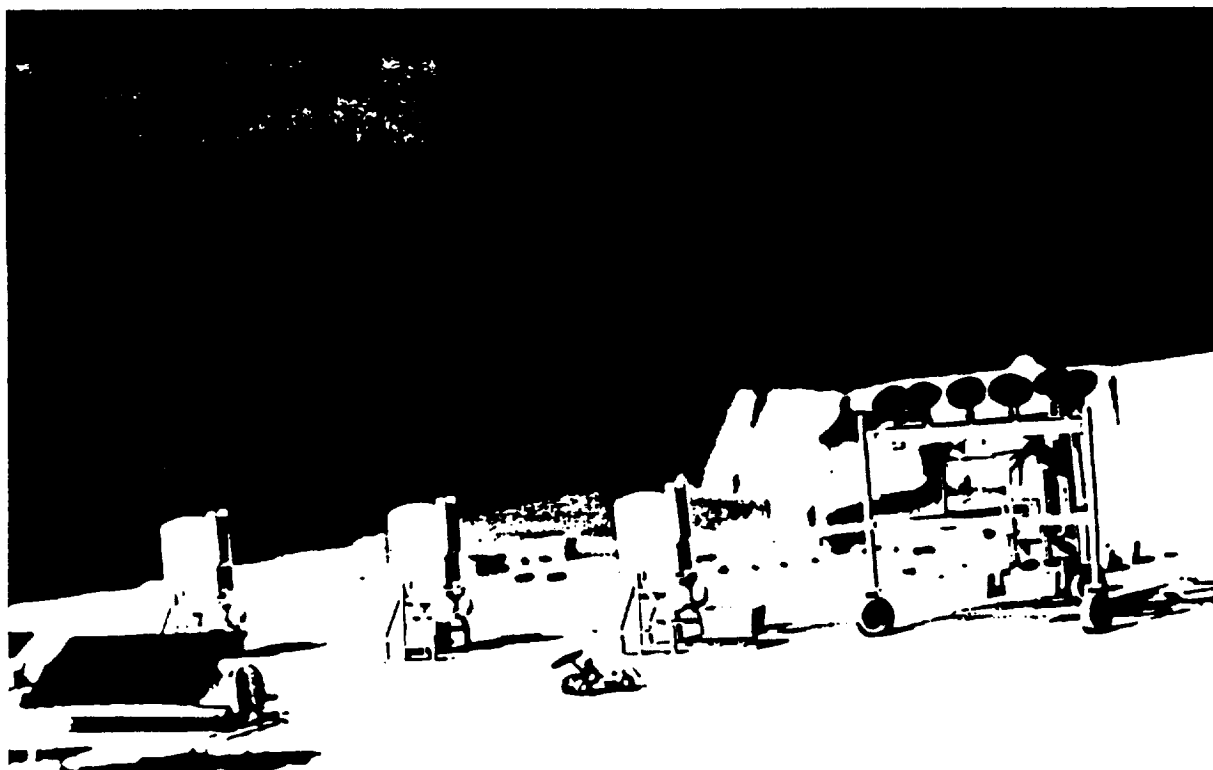
CHARACTERIZATION OF PMAD SYSTEM FOR ADVANCED LUNAR BASE APPLICATION

The specific mass of the PMAD system was assumed to be an order of magnitude heavier than the components itself. This is due to the fact that the total PMAD system must include triple redundancy (triple power buss), smart electronics to detect failures, sensors, cables, and radiators, in addition to the electrical components (capacitors, transformers, inverters, etc...).

At the low power levels, 20 KHz technology performance was assumed. This technology was developed by NASA LeRC in early 80's and was previously envisioned to be utilized for SSF. At the multimegawatt level, we assumed the performance of technology currently under development by NASA LeRC under the sponsorship of SDIO, which calls for multimegawatt, high temperature (> 200 C°) electronics.
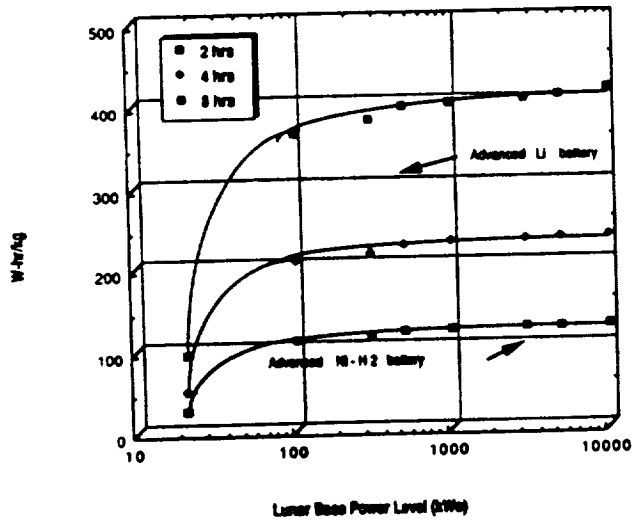
MASS OF RFCs USED AS BACKUP POWER SYSTEM

RFC Mass (Tonnes)

1000
100
10
1

10   100   1000   10000

Lunar Base Power Level (kWe)

- 2 hrs
- 4 hrs
- 8 hrs

This is the scaling of an RFC assuming cryo storage. At the high power levels the dominant portion of the total RFC mass is power dependent. This might not be the case for a 336 hrs. storage requirement at the same power level.
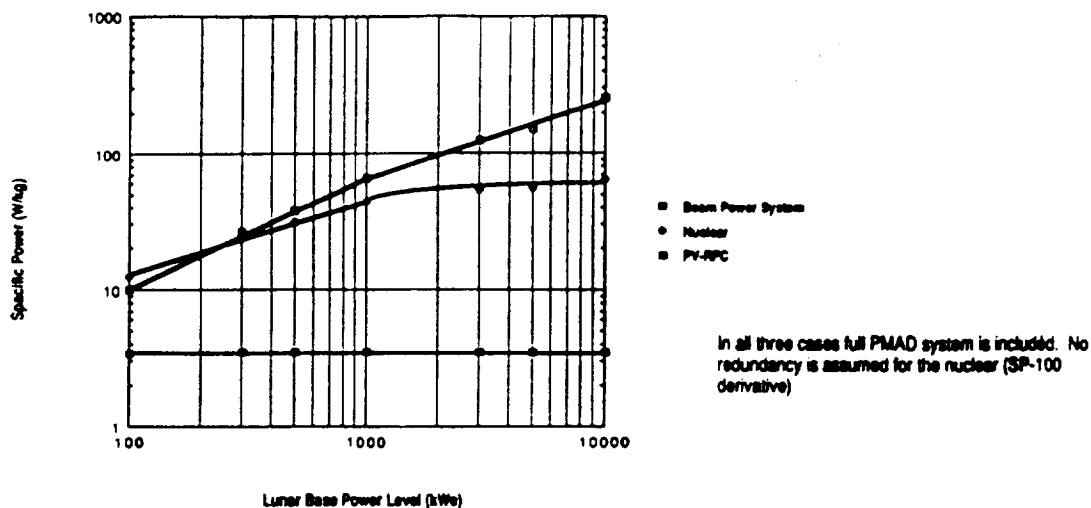
SPECIFIC MASS OF RFCs FOR SURFACE BACKUP POWER SYSTEMS

W-hr/kg

500
400
300
200
100
0

10   100   1000   10000

Lunar Base Power Level (kWe)

- 2 hrs
- 4 hrs
- 8 hrs

Advanced Li battery

Advanced Ni-H2 battery

Comparison of RFC specific mass with other conventional energy storage devices.

Specific Power (W/kg)

Lunar Base Power Level (kWe)

- Beam Power System
- Nuclear
- PV-RPC

In all three cases full PMAD system is included. No
redundancy is assumed for the nuclear (SP-100
derivative)

CONCLUSIONS:

The idea of beaming power from the ground up is not new at all. The reader
could easily find literally hundreds of articles covering this subject,
particularly power beaming to orbital maneuvering vehicles (OTV's), laser
boost to orbit, and spaceborne weapon systems (area heavily sponsored by
SDIO). With the knowledge acquired by all these experiences, i.e.,
technology developed, we are confident a beam power system to beam
power to the surface of the Moon is feasible within the next 5 to 6 years,
depending upon availability of funding, at a very competitive price, when
compare to the cost of more conventional approaches.

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